AN INVESTIGATION OF THIN LUBRICANT FILMS UNDER LOW SHEAR RATES

LAWRENCE SHAFER

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by

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Lieutenant, United States Navy

Submitted in partial fulfillment of
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IN
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ABSTRACT

Thin squeeze films of lubricating oils were investigated under low shear rates. The oils were squeezed between two circular mirrored discs under light static loads. The variation in thickness of the films with time was obtained by interferometric measurement. Data for films between 17 microns and one-half micron in thickness was obtained. Evidence of increased viscosity was observed in films up to nine microns in thickness. The thickness at which increased viscosity was observed did not vary with load or shear rate, but did depend upon the oil, character of solid boundary, and size of the squeezing surfaces.

Stable film thicknesses which varied inversely with load were observed for oils left under load up to 72 hours. The stable films recovered slowly in thickness upon removal of portions of the load.

The experimental work was performed at the U. S. Naval Postgraduate School, Monterey, California during the winter and spring of 1959.

The writer expresses his appreciation to Professor Ernest K. Gatcombe of the U. S. Naval Postgraduate School for his advice and encouragement. Thanks are also due to Professor Gilbert F. Kinney for his assistance, and to Mr. Robert C. Moeller of the Postgraduate School for the preparation of the mirrors used in the investigation.

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TABLE OF SYMBOLS AND ABBREVIATIONS

Btu	British Thermal Unit
C.	Degrees Centigrade
F.	Degrees Fahrenheit
J	Joule's Equivalent = 778.26 ft.-lbs./Btu
M	Mass of load on lubricant film (gm.)
N	Number of dark fringes in interferometer spectrum included between blue and green mercury spectral lines
P	Force exerted by lubricant against one solid boundary (dynes)
R	Radius of interferometer mirror (cm.)
T	Temperature
V	Volume of fluid (cc.)
W	Weight of load on lubricant film = Mg (dynes)
c	Radial velocity of lubricant (cm./sec.)
cc.	Cubic centimeters
c_p	Specific heat of lubricant (Btu/lbm.-F.)
cm.	Centimeters
ft.	Foot
g	Gravitational acceleration (cm./sec.^{2})
gm.	Grams
h	Lubricant film thickness, or separation of interferometer mirrors (cm.)
lb.	Pounds force
lbm.	Pounds mass
n	Fringe order (an integer)
p	Average pressure at a point in the lubricant (dynes/cm.^{2})

TABLE OF SYMBOLS AND ABBREVIATIONS

psi	Pounds per square inch
r	Radial coordinate (cm.)
sec.	Second
t	Time (sec.)
x	Horizontal coordinate (cm.)
y	Horizontal coordinate (cm.)
z	Vertical coordinate (cm.)
Δ	Increment of
δ	Phase lag
η	Index of refraction
θ	Angle of incidence of light
λ	Wavelength (microns)
μ	Viscosity of lubricant (poises)
π	3.1416...
ρ	Density of lubricant (lbm./ft.^{3})

1. Introduction.

The fundamentals of hydrodynamic lubrication were established by the pioneer work of Osborne Reynolds in 1886. Hydrodynamic theory has been a powerful tool in the analysis of lubricant action. However, under a great many conditions of operation, full hydrodynamic lubrication cannot be maintained. This is especially true where the thickness of the lubricant layer separating adjacent parts is very small. Under these conditions, lubricant behavior may well depend on properties other than the bulk viscosity alone.

In the application of simple hydrodynamic theory to the flow of liquids, it is generally assumed that a layer of liquid adjacent to the solid boundaries is held immobile. There is considerable experimental evidence that such a layer does indeed exist. Furthermore, the thickness of this immobile layer appears to be appreciably greater than that of a lubricant molecule. If this is true, then it might be expected that the behavior of a very thin lubricant layer would be greatly influenced by the properties of the boundary layer. Investigations of boundary layers may furnish the basis for a theory which would be valid where conventional hydrodynamic theory does not account for lubricant action.

Investigations into the physical chemistry of lubricants have shown that, under certain conditions, adsorption can take place at a solid boundary, with a preferential

orientation of lubricant molecules near the boundary (1,2). It has also been found that low concentrations of certain polymerizing agents can exert large effects upon interfacial activity without noticeably affecting the bulk properties of the lubricants.

The data of Gatcombe, Hunnicutt, and Kinney (3), Tausz and Szekely (4), and others (1), show that the apparent viscosity of lubricating oils increases near a solid boundary, and that reduced mobility exists in a layer of appreciable thickness. The effects observed by these investigators cannot be fully explained by the presence of dirt or surface asperities because polymeric lubricants show a greater boundary layer thickness in which increased voscosity exists (5).

In the investigations referred to above, the results seem to be a function of the methods employed in their determination. The means of measurement, surface asperities, and foriegn matter on the surfaces or in the lubricants may all have contributed to differences in the data obtained. The detection of immobilized layers also seems to be dependent upon the shear or shear rate employed. This might be of primary importance, since the maximum shear stress at which a boundary layer of given thickness can be observed may be a measure of its mechanical strength and practical significance.

It was the purpose of this investigation to attempt to shed more light upon the behavior and properties of lubri-

cants in thin films. The experimental equipment employed for this purpose limited the range of shear and shear rates attained to low values. While this limited the scope of the investigation, it is believed that the data compiled is useful as a piece of basic research in boundary lubrication, and may find application in situations where low shear rates are encountered.

The method of investigation consisted of squeezing lubricating oils between flat surfaces under the action of dead weights. The decrease in the thickness of the lubricant layer with time was obtained by optically measuring the separation between the solid surfaces. The behavior of the lubricant under these conditions was then compared with the predictions of simple hydrodynamic theory.

2. Apparatus.

The lubricant to be tested was placed between two discs of optical glass which comprised a type of Fabry-Perot interferometer. The lubricant was loaded by weights acting through a circular knife edge as shown in Fig. 1. The flat surfaces of the discs were ground and polished to within one-tenth of the wavelength of visible light, or about 0.05 microns. The surfaces adjacent to the lubricant were mirrored by coating them with a thin film of metal by means of thermal evaporation.

Two sets of interferometer discs were used in the experiments. One set had a radius of 0.50 inches or 1.27

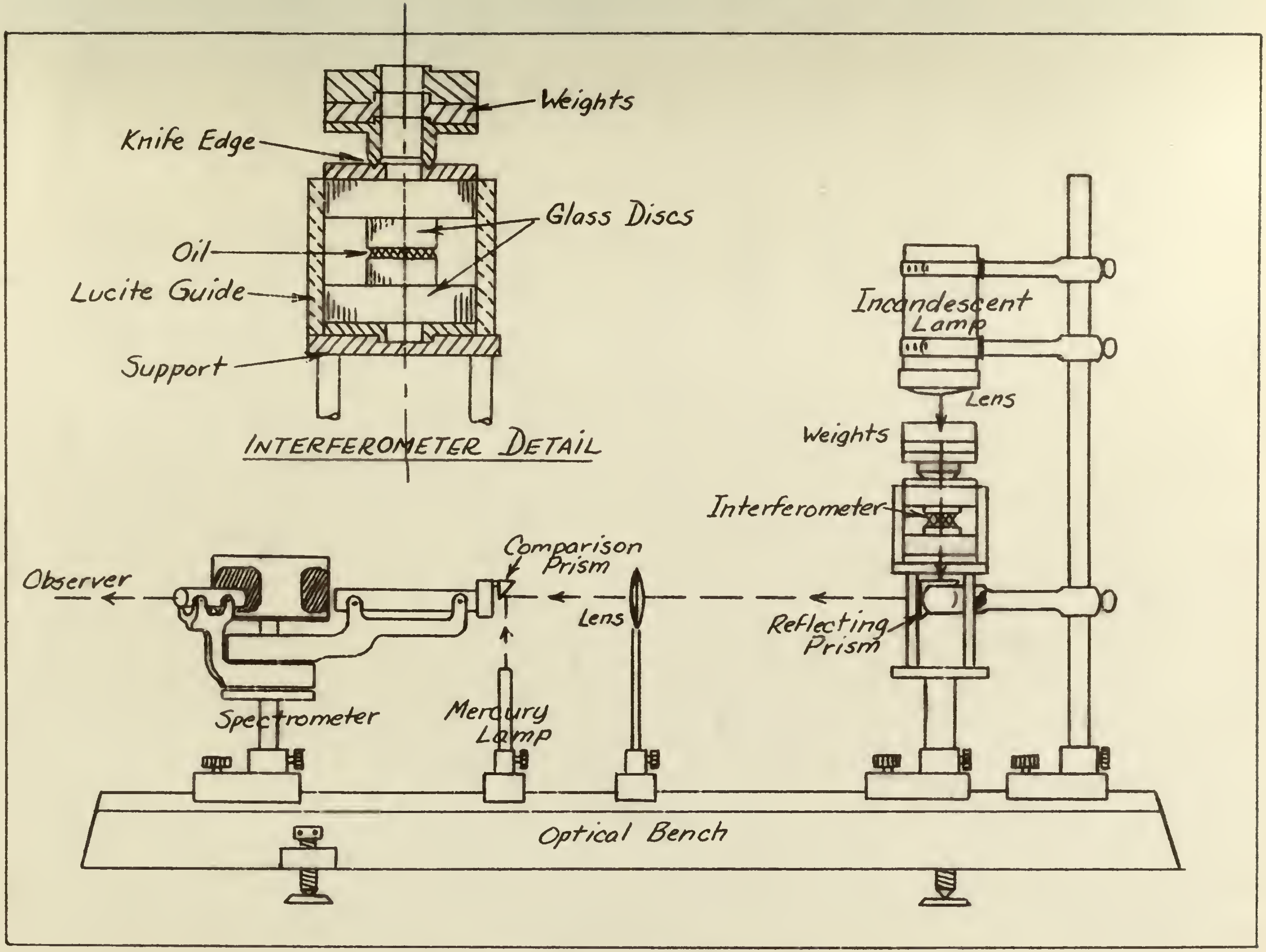

FIGURE 1. Apparatus.

centimeters. The mirrored surfaces of these discs were coated with silver. A thin film of calcium fluoride was evaporated over the silver to protect the surface from oxidation and abrasion. As freshly prepared, the upper (moving) disc exhibited 43% transmission of incident light, and the lower disc transmitted 48% of incident light. The total coating thickness, as freshly prepared, was estimated to be about 0.05 microns or less (6).

The other set of interferometer discs had a radius of 0.375 inches or 0.953 centimeters. These discs had been used extensively in a previous investigation. The mirrored surfaces were coated with aluminum. The transmissivity and coating thickness were estimated to be approximately the same as for the silvered mirrors.

An approximately parallel light beam from an incandescent source was passed through the interferometer at about normal incidence to the mirrored surfaces. The beam was then directed upon the slit of a prism spectrometer through a system of reflecting prisms and lenses as shown in Fig. 1. This produced a "channeled" spectrum in which interference fringes appeared equally spaced.

By means of a comparison prism mounted in front of the spectrometer slit, a reference spectrum from a mercury lamp was superimposed upon the interferometer spectrum. The appearance of these two spectra in the objective of the spectrometer telescope is illustrated in Fig. 2.

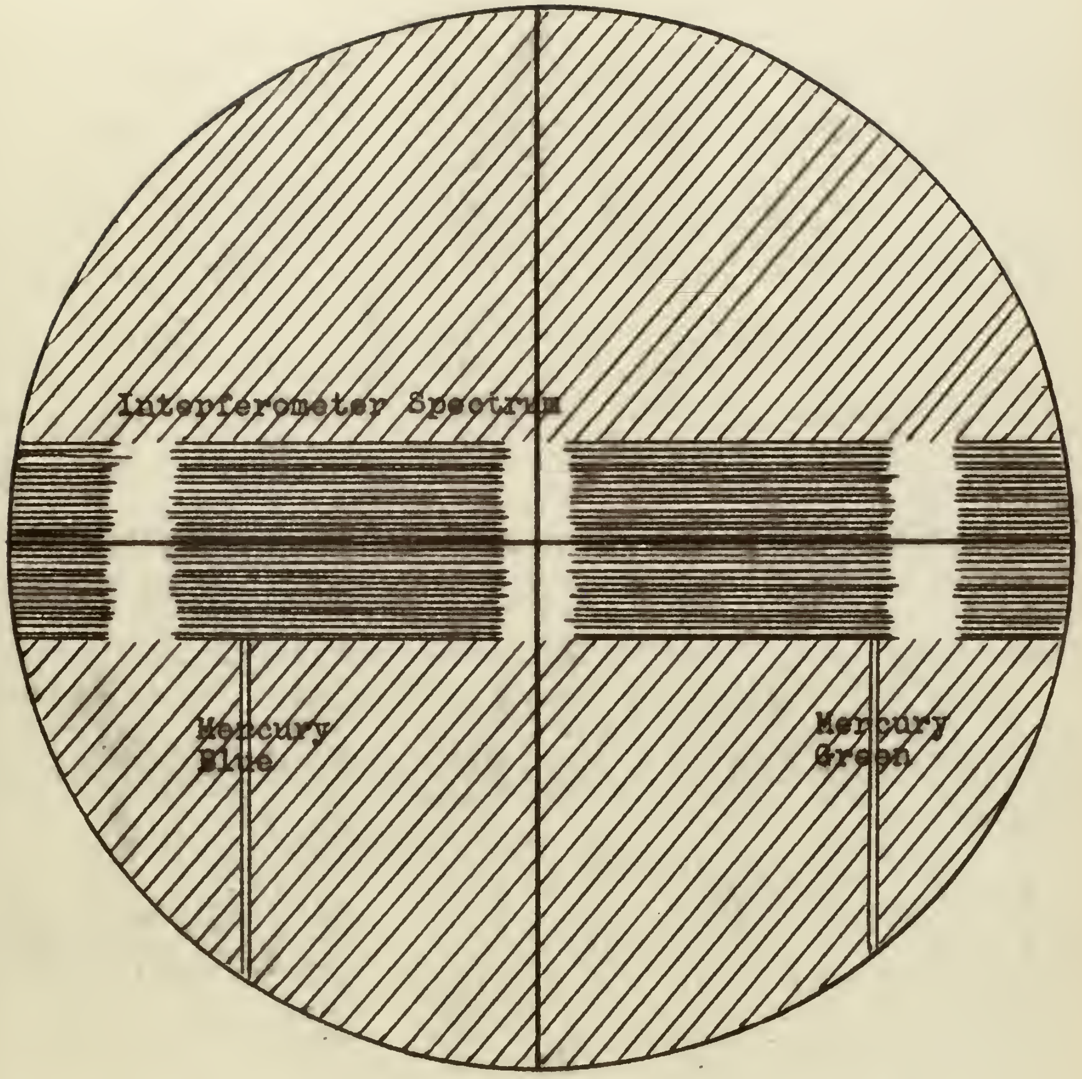

FIGURE 2. View through spectrometer telescope showing spectra from interferometer and Mercury lamp.

To facilitate gathering data, the experimenter talked his observations into a tape recorder. The tape was played back when convenient and the times of the observations were noted.

3. Experimental Procedure and Data Reduction.

At the commencement of a run, the experimenter placed an oil film between the interferometer discs and placed the desired load upon it. The vertical cross-hair in the spectrometer telescope was set on the green line of the mercury reference spectrum. The experimenter said "mark" into the recorder microphone as each bright fringe of the interferometer spectrum passed the vertical cross-hair. The horizontal cross-hair was adjusted to bisect the interferometer spectrum so that readings could be made at the same point on each fringe, wheter or not it was strictly vertical.

When the movement of the fringes was imperceptible, the experimenter counted the number of dark fringes (N) between the blue and green mercury lines by making several traverses of this area using the horizontal adjustment screw on the spectrometer telescope.

This primary data was reduced to give film thickness versus time by means of the relations derived below:

The path difference between successive beams in a parallel mirror interferometer is $2\eta h \cos \theta$, where η is the index of refraction of the medium separating the mirrors, h is the mirror separation, and θ is the angle of incidence

of the light (6). For normal incidence, each beam has a phase lag δ given by:

$$\delta = \frac{2\pi \cdot 2\eta h}{\lambda}$$

where λ is the wavelength. Maximum transmission occurs where $\delta = 2\pi n$, where n is an integer. Thus, if a bright fringe is transmitted at the wavelength of the green mercury line (0.5461 microns) at a time t:

$$0.5461\, n = 2\eta\, h(t)$$

If the interferometer gap h is steadily closing, abright fringe will again be transmitted at this wavelength after a time interval Δt. Thus:

$$0.5461\,(n-1) = 2\eta\, h(t+\Delta t)$$

During the time Δt, h has decreased by an amount $\Delta h = h(t) - h(t + \Delta t)$, or

$$\Delta h = -0.5461/2\eta \qquad \text{...............1}$$

This is the change in thickness during the time for successive bright fringes to cross the mercury green line.

If h is constant, and a bright fringe is transmitted at 0.5461 microns, $0.5461\ n = 2\eta h$. If N is the number of dark fringes between the mercury green line (0.5461 microns) and the blue mercury line (0.4358 microns), the fringe order at the blue mercury line (n + N) is related to h by: $0.4358\ (n + N) = 2\eta h$. Therefore, the interferometer gap h is related to N by:

$$h = \frac{(0.5461 \times 0.4358)\, N}{2\eta\ (0.5461-0.4358)} = \frac{1.0788}{\eta} N \qquad \text{..........2}$$

The thickness of the oil film for the final data point of each run was computed by equation 2. The preceding thicknesses were calculated by successive additions of h as computed by equation 1.

Equation 2 is not strictly accurate when applied to silvered mirrors. There is a phase change of light at the silver reflecting surface which depends upon wavelength. There is no appreciable effect in the green region, but fringes transmitted at the blue end of the spectrum may be displace perhaps two-tenths of a wavelength. The fringe spacing is consequently slightly wider at the blue end of the spectrum than it is in the green region. This effect is not present when the reflecting surface is aluminum.

4. Preparation of Oil Films.

No attempt was made to purify the oils used, except that the #10 S. A. E. oil was centrifuged for 30 minutes at 10 gravities by the supplier. Oil properties are tabulated in Appendix I. Each sample was stored in a screw-top can and handled only under a hood fitted with an exhaust blower. Samples were transferred with a pipette degreased in trichloroethylene vapor.

Before applying oil to the interferometer surfaces, the mirrors were bathed in benzene and then vapor degreased in trichloroethylene under the hood to remove dirt and any residual oils from previous runs. When the interferometer was not assembled, the discs were always kept and transported in

in covered Petri dishes. After cleaning, the discs were examined under the microscope using light at grazing incidence. Any foriegn particles which could be detected under 25 magnifications were removed with a clean camel's-hair brush. This microscopic examination was abandoned for the last eight runs with the silvered mirrors when experiment indicated that the data could be reproduced without taking this extra precaution.

When the mirrors were clean, a drop or two of oil was placed upon the bottom mirror. The interferometer was assembled immediately, placed in the apparatus, and data taking commenced.

5. Data Analysis.

It was desired to compare the behavior of the lubricants tested with the behavior predicted by the hydrodynamic theory. A solution for the flow of liquid between two parallel surfaces approaching each other was advanced by Osborne Reynolds (7,8). This solution was adapted to analyzing the experimental data.

Referring to Fig. 3, the Navier-Stokes equations can be simplified to:

$$\partial p/\partial z = 0$$

$$\partial p/\partial r = \mu\, \partial^2 c/\partial z^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots 3$$

where flow takes place between two planes bounded by the curve $x^2 + y^2 = R^2$, p is the average pressure at a point, μ is the viscosity of the fluid, c is the (radial) velocity

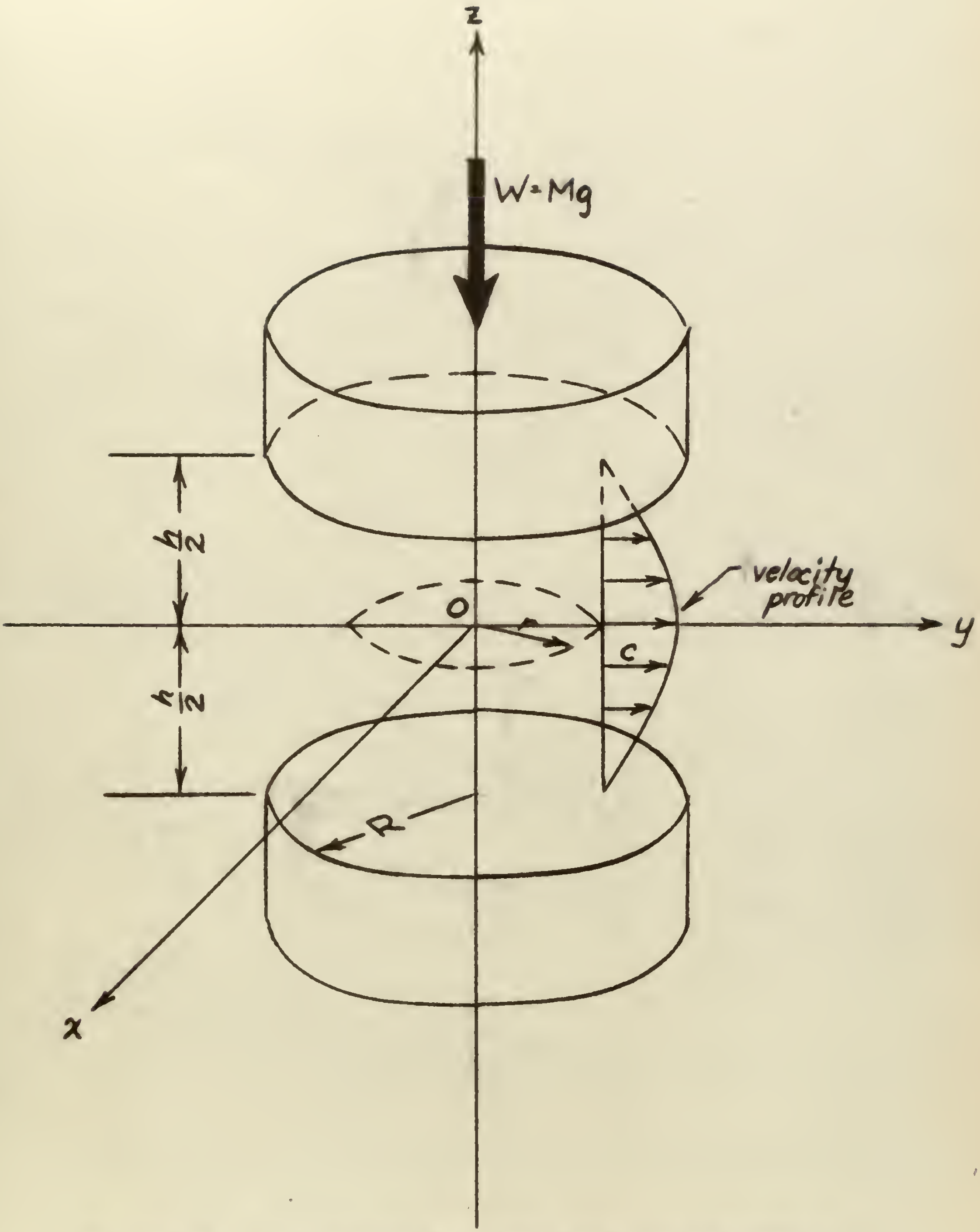

FIGURE 3. Coordinate system for hydrodynamic theory solution of oil flow between interferometer discs.

in a plane perpendicular to the z-axis, and z and r are coordinates illustrated in the figure. To reduce the equations to this form, the flow velocity in the z-direction has been neglected as compared with the velocity of radial flow. Also, the second derivative of the radial velocity in the x or y-directions has been neglected. The fluid viscosity has been assumed to be constant, and the fluid treated as being incompressible.

Equation 3 can be integrated directly, using the boundary conditions that c = 0 for z = ± h/2:

$$c = \frac{1}{2\mu} \frac{\partial p}{\partial r} \left(z^2 - \frac{h^2}{4} \right)$$

The volume of liquid swept out in a time interval Δt is:

$$\Delta V = 2\pi r h \int_{-h/2}^{h/2} c\,dz \cdot \Delta t = \pi r^2 \frac{dh}{dt} \cdot \Delta t$$

or,

$$\int_{-h/2}^{h/2} c\,dz = \frac{1}{2\mu} \frac{\partial p}{\partial r} \int_{-h/2}^{h/2} \left(z^2 - \frac{h^2}{4} \right) dz = \frac{r}{2h} \frac{dh}{dt}$$

$$\frac{\partial p}{\partial r} = \frac{6\mu}{h^3} r \frac{dh}{dt}$$

The pressure distribution is, then:

$$p = \int_r^R \frac{\partial p}{\partial r} dr = \frac{6\mu}{h^3} \frac{dh}{dt} \int_r^R r\,dr = \frac{3\mu}{h^3} \frac{dh}{dt} (R^2 - r^2) \quad \ldots .4$$

So that the total force exerted by the fluid upon the upper disc is:

$$P = \int_0^R p \cdot 2\pi r\,dr = \frac{6\pi\mu}{h^3} \frac{dh}{dt} \int_0^R (R^2 - r^2) r\,dr = -\frac{3\pi\mu R^4}{2h^3} \frac{dh}{dt}.$$

If the upper disc is descending under its own weight W, its acceleration can be neglected. Equating W to P:

$$\frac{dh}{dt} = \frac{-2W}{3\pi\mu R^4} h^3 \qquad \text{.................5}$$

$$\frac{d(1/h^2)}{dt} = \frac{4W}{3\pi\mu R^4} \qquad \text{.................6}$$

Equation 6 states that a plot of time against inverse film thickness squared will be a straight line whose slope depends upon oil viscosity, load, and radius of the discs. These plots were made as part of the data analysis.

6. Experimental Errors.

One source of experimental error results from the fact that the interferometer spectrum is very sensitive to small deviations of the mirrors from parallelism. The result of such deviations is to slant and warp the fringes away from the horizontal. Often, the fringes observed made angles of 45 degrees or more with the vertical. This made accurate estimation of primary rate data and final film thicknesses more difficult by effectively increasing the width of the fringes in the horizontal direction. If there were many fine fringes, the fringe slant was not troublesome in observing the time a bright fringe passed the mercury green line. But when the fringes were few and broad, the possible error in estimating the total number of fringes included between the green and blue lines of the mercury spectrum was as much as two-tenths of a fringe at times. This held especially

true under heavy loads, because the fringes were fewer in number, and the bright and dark fringes were wider. The silvered mirrors gave sharper contrast between bright and dark fringes. Consequently, the spectrum from these mirrors was more easily and accurately read.

However, in another respect, the silvered mirrors were inferior to the discs coated with aluminum. The fringes were not evenly spaced due to a phase change at the silver reflecting surface which varied with wavelength. This has been mentioned in section 3. Interference fringes in the blue region of the spectrum were spaced more widely than in the green region. The difference in separation varied inversely with the number of fringes, and led to a maximum error of perhaps two-tenths of a fringe in estimating the total number between the mercury reference lines.

The combined effect of the two sources of error discussed above was to produce a constant error in the film thicknesses calculated for any given run varying from about 0.08 microns for light loads up to about 0.30 microns for heavy loads.

Due to the difficulty in reading the interferometer spectrum for the reasons given above, and to the use of voice and tape recorder to take the data, a slight error in the times of observations was introduced. This error was not more than two seconds between any two data points in a given run. In the initial phases of a run, where the velocities

were greater, this error was not more than one second. No difficulty was experienced in timing data points at half-second intervals.

Another source of error arose from the condition and cleanliness of the mirror surfaces. The silver mirrors showed marked damage after the first four runs, with continuing lesser damage afterward. Most of the damage seemed to occur when the discs were separated for cleaning. Areas of silver were stripped off, leaving valleys and ridges. The aluminum mirrors had seen use in previous work and were damaged from the start. It was impossible to ascertain whether subsequent use removed any more aluminum. Figs. 22 and 23 show the mirror surfaces upon completion of the experiments. The surface damage did not confuse the spectrum. The effect upon lubricant flow is discussed in section 8.

7. Description of Results.

Figures 4 through 10 present the data representing the transient behavior of the oils tested. These data are plotted as time versus the square of the inverse oil film thickness for comparison with the hydrodynamic theory solution. From equation 6, these curves are predicted to be straight lines, with slopes proportional to the load. For a given oil between a given set of discs, the slope should be inversely proportional to the load upon the oil film. The initial portions of these curves indicate general agreement with the hydrodynamic theory solution. However, at some point, the

curves deviate upward from a straight line. This increase in slope indicates an increase in the apparent viscosity of the oils. The curves all tend toward an infinite slope, indicating that the oils approach a "stable" film thickness which appears to vary directly with the load intensity.

By plotting these data curves to a much larger scale, a more interesting phenomenon is evidenced. Figures 11 through 20 show "blown up" sections of the time - $(1/h^2)$ curves. With very few exceptions, the "knee" of the curve is the same value of $(1/h^2)$ for a particular oil in a particular interferometer. This point of apparent increased viscosity will be dubbed the "critical" film thickness h_c. It will be noted that for a given oil h_c is independent of the load. The following table summarizes the data read from Figures 11 through 20:

TABLE I

"CRITICAL" FILM THICKNESSES, h_c

Oil, SAE Number	Mirror Surface	Radius of Mirror (cm.)	$(1/h_c^2) \times 10^{-6}$ (cm.$^{-2}$)	h_c (microns)
10	Silver	1.27	4.75	4.58
20	"	"	3.00	5.76
30	"	"	2.85	5.92
50	"	"	1.60	7.90
20	Aluminum	0.953	2.60	6.20
30	"	"	1.90	7.25
50	"	"	1.25	8.93

Load Range (Silvered Discs): 105.5 to 1176.8 gm.
Load Range (Aluminized Discs): 95.8 to 169.7 gm.

A series of experiments were conducted to determine the stable film thickness obtained for various loads. The data is presented in Fig. 21, which gives the stable film thickness as a function of nominal load pressure. The nominal load pressure was computed as the total load divided by the surface area of the mirror in contact with the oil. The loads embrace the range used in the transient behavior tests, and include some heavier loads. The data is tabulated in App. III.

To obtain stable values, oil films were left under load for periods varying from one hour to 72 hours. As well as could be determined, stable thicknesses were reached in two hours or less. For some data points, freshly prepared oil films were used. Other stable thicknesses were obtained by adding loads to oil films which had already attained a stable thickness under a lighter loading.

The data in Fig. 21 shows considerable scatter. However, it can be seen that the stable film thickness decreases for heavier loads. The stable values lie in the range from one-half to two microns for the most part. The possible errors in measurement discussed in the preceding section make it impossible to clearly distinguish the effects of oil viscosity, type of metal surface, or geometry of the surface.

Upon unloading these stable films, "relaxation" akin to the memory of plastics was observed. That is, the oils slowly recovered a portion of their original thickness. Most of this recovery took place in ten minutes or so.

TABLE II

RELAXATION (BULK RECOVERY UPON RELEASE OF LOAD)

Oil, SAE No.	Mirror	Mass of Load (gm.)	Nominal Load Pressure (psi)	Stable Film Thickness (microns)	Relaxed to (psi)	Time Observed (min.)	Thickness (microns)
20	Ag	2684.8	7.55	1.23	0.30	5	1.52
20	Al	2275.1	11.38	0.73	0.03	3hrs.	1.16
50	Ag	2684.8	7.55	1.16	0.30	72hrs.	1.52
50	Al	2275.1	11.38	0.72	0.05	10	1.09

To check upon the stable film thicknesses obtained, the interferometer was assembled, after cleaning, with no oil film inserted between the mirrors. As the data in Table III indicates, the mirrors showed a large separation, even under load. When loads were removed, the mirror separation became wider. However, this recovery took place instantaneously. No gradual relaxation could be detected, although the mirrors remained up to two hours under load.

TABLE III

INTERFEROMETER BEHAVIOR WITHOUT OIL FILM ON MIRRORS

Mirror	Radius	Load Mass	Interferometer Gap
		101.5 gm.	3.2 microns
Silver	1.27 cm.	1176.8 "	3.2 "
		2684.8 "	2.2 "
		101.5 "	2.8 " (recovery)
		6.4 gm.	2.2 microns
Aluminum	0.953 cm.	163.5 "	2.1 "
		747.1 "	1.0 "
		311.6 "	1.0 " (recovery)
		9.4 "	1.4 " (recovery)

These results were consistently reproducible, even

after the mirrors were meticulously cleaned and showed no foriegn particles when examined under 25 magnifications with light at grazing incidence. However, subsequent examination using a metallurgical microscope and 100 magnifications revealed some foriegn matter with dimensions of perhaps one to two microns. Surface asperities could not be seen clearly. Figs. 22 and 23 are photomicrographs of the mirror surfaces magnified 100 times.

The interferometer gap measured without oil between the mirrors is greater at all loads than the stable oil film thicknesses obtained. It seems probable, therefore, that the oil floats out dirt and permits the mirrors to approach one another more closely.

8. Discussion of Results.

The significance of the results presented in Figs. 11 through 20 (plots of time versus inverse film thickness squared) depends upon the validity of equation 6:

$$\frac{d(1/h^2)}{dt} = \frac{4W}{3\pi\mu R^4} \qquad \cdots\cdots\cdots\cdots\cdots\cdots 6$$

All of the assumptions as to the character of the flow which were made in deriving equation 6 are open to question, particularly when the film thickness is quite small and surface asperities and/or foriegn matter could exert large disturbing effects. However, the slopes of the straight line portions of the plots follow the predictions of the equation reasonably well. Also, the point of deviation from the straight line follows a regular pattern

The deviation of these curves from a straight line cannot be attributed to either pressure or temperature effects. The maximum pressure can be calculated by combining equations 4 and 5:

$$p = \frac{3\mu}{h^3}\frac{dh}{dt}(R^2 - r^2) \quad \ldots\ldots\ldots\ldots\ldots 4$$

$$\frac{dh}{dt} = \frac{-2W}{3\pi\mu R^4}h^3 \quad \ldots\ldots\ldots\ldots\ldots 5$$

$$p_{max.} = \frac{-2W}{\pi R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots 7$$

The value given by equation 7 does not exceed seven pounds per square inch for any run. The effect of such a low pressure in deforming the solid surface or in changing the viscosity of the oil can be neglected.

The temperature rise of the oil due to viscous heating can be estimated by assuming that all of the work done in squeezing the oil to a stable thickness is absorbed as heat by the volume of oil remaining. The work done per unit volume is $\frac{2}{3} p_{max} \Delta h$. Using a maximum value for the average pressure of five pounds per square inch, a total change in thickness Δh of 30 microns, a stable thickness h of one-half micron, a specific heat c_p of 0.5 Btu/lbm.-F., and an oil density ρ of 53 lbm/ft.^{3}, the maximum temperature rise is estimated to be:

$$\Delta T_{max.} = \frac{p_{avg.} \cdot \Delta h}{c_p J \rho h} = \frac{(5 \times 144) \times 30}{0.5 \times 778 \times 53 \times 0.5} = 2^\circ F.$$

The estimate is generous and can be safely neglected as far as temperature effects on viscosity or refractive index go.

It can be stated then, that the lubricants tested exhibited a departure from hydrodynamic behavior in film thicknesses of about four to nine microns. The change in behavior indicated an increase in viscosity. The heavier oils exhibited this phenomenon at greater film thicknesses than the lighter oils. Oils tested between aluminum surfaces of smaller surface area exhibited this behavior at greater film thicknesses than those tested between silver surfaces of greater surface area. However, the magnitude of the differences involved is about the same order as that of the possible errors in measurement. Still, the effect is consistent, and may be due to geometry, surface material, or surface roughness. Dirt effects and surface asperities which may have contributed to this phenomenon would, of course, be expected to be present under service conditions. The depth at which increased apparent viscosity is detected is independent of shear or shear rate in the range employed in the tests. This may be an indication that boundary conditioned layers several microns in thickness exist at all times, and do not form just when the total lubricant thickness is reduced under the action of a load.

Deryaguin and his associates (5) have proposed a two-term law of static friction in which the friction force depends upon both the load and the area of real or molecular

contact. Others, such as Bowden and Tabor (9), hold the view that only the area of molecular contact influences the friction force. If the coefficient of static friction is connected with a boundary-conditioned layer, the edge of which is indicated by the characteristic "knee" in the time-($1/h^2$) curves, the invariance of the layer thickness with load does not coincide with the theories of Deryaguin unless the properties of the boundary layer vary with changes in load.

Deryaguin (5) states:

> The resistance to shear is brought about by a normal load on the film, and appears and disappears with the load.

This assumed property of the boundary film reconciles the inferences above with the two-term friction law Deryaguin proposed.

Each of the oils tested reached a stable film thickness which varied inversely with the load. These stable films exhibited a "relaxation" or recovery upon release of load. The term "relaxation" as used herein refers to a bulk property akin to the memory of plastics, and not to atomic or molecular phenomena to which it is sometimes applied. The accuracy with which these stable film thicknesses were measured does not permit conclusions to be drawn as to the effect of type of oil, surface roughness, foriegn matter, or geometry upon the stable film thickness attained. Any or all of these factors could conceivably affect the results.

The thinnest stable film thickness observed was about 0.7 microns under a load of about five pounds on a surface of 0.44 square inches. This thickness may well be about the same as that of surface asperities and/or included foriegn matter.

In comparing the results of these experiments to those obtained by other investigators, it should be borne in mind that the oils were included between two solid surfaces. That is, two boundary layers are present, one at each surface. The film thicknesses referred to in this paper might thus be expected to be greater than those found by experiments in which only one solid boundary is involved.

9. Summary.

In summation, the oils tested showed a behavior which indicated increased viscosity in thicknesses from 0.7 to nine microns under the special conditions of the tests. These thicknesses are greater than those observed by most other investigators. These results were obtained for oils squeezed between two solid boundaries under low shear and shear rates. Factors which influence this phenomenon may be:

(a) Weight of oil.

(b) Foriegn matter.

(c) Surface roughness.

(d) Surface material

(e) Geometry.

The thickness of the layer of increased viscosity showed no variation with shear or shear rate.

The engineering significance of what appear to be boundary-conditioned oil layers may depend upon their existence and properties under heavy loads and under dynamic conditions of loading. They probably influence lubricant behavior at low shear rates, and affect static friction between lubricated surfaces.

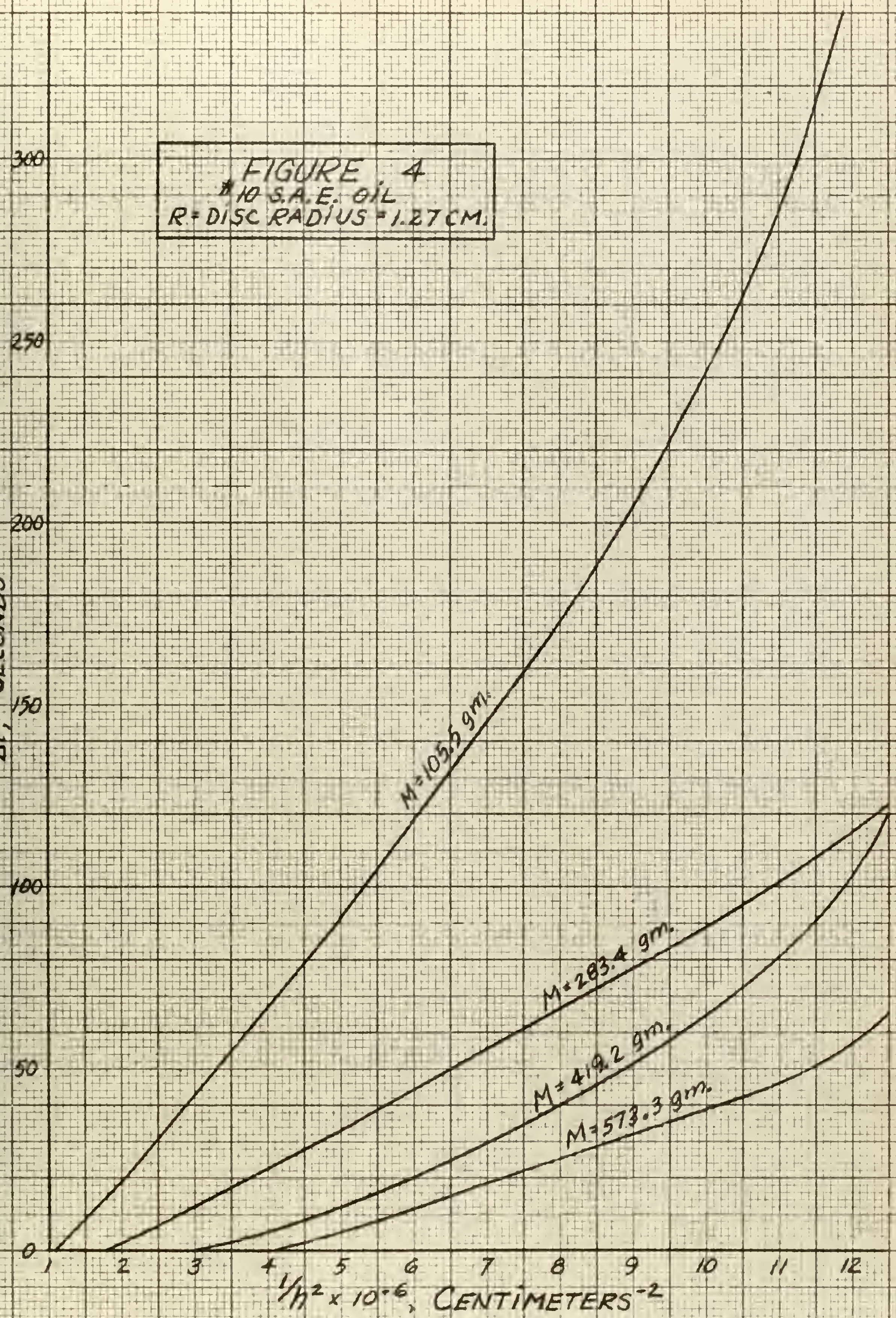
FIGURE 4
#10 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
Δt, SECONDS
300
250
200
150
100
50
0
M = 105.5 gm.
M = 283.4 gm.
M = 419.2 gm.
M = 573.3 gm.
1
2
3
4
5
6
7
8
9
10
11
12
1/h² x 10⁻⁶, CENTIMETERS⁻²

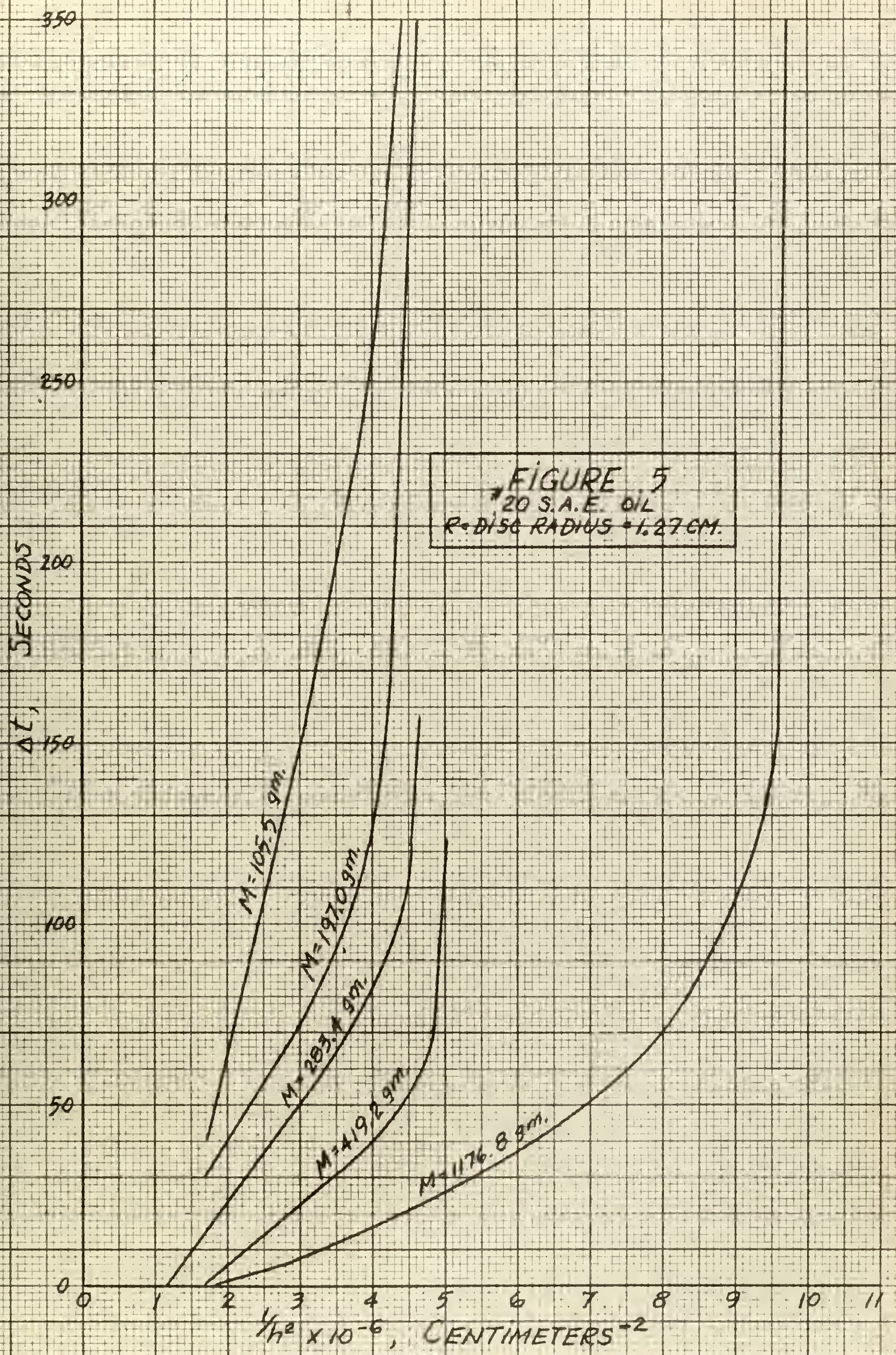

FIGURE 5
#20 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
M=105.5 gm.
M=197.0 gm.
M=283.4 gm.
M=419.2 gm.
M=1176.8 gm.
Δt, SECONDS
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11
1/h² x 10⁻⁶, CENTIMETERS⁻²

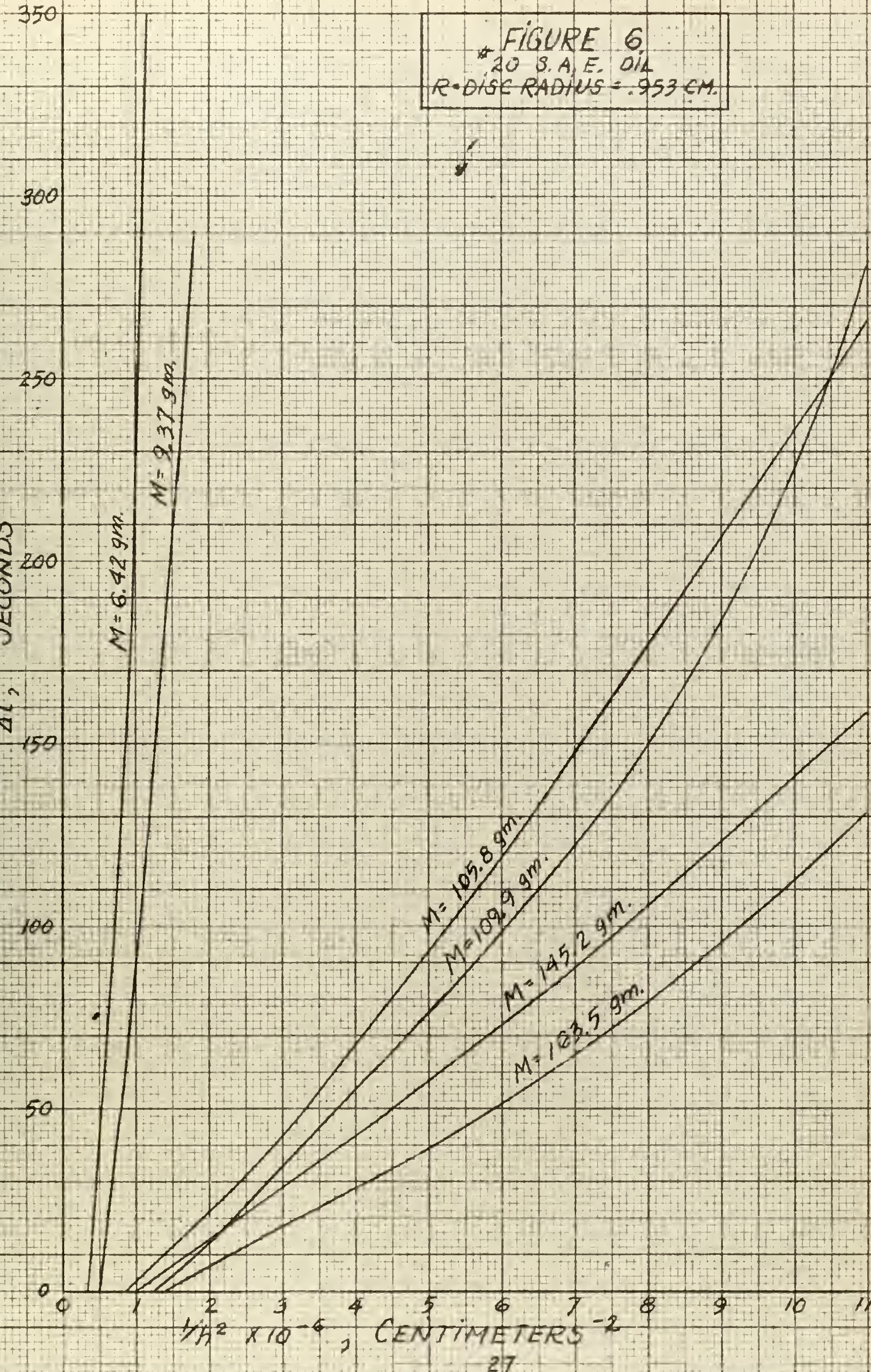
FIGURE 6
#20 S.A.E. OIL
R = DISC RADIUS = .953 CM.
M = 6.42 gm.
M = 9.37 gm.
M = 105.8 gm.
M = 109.9 gm.
M = 145.2 gm.
M = 183.5 gm.
Δt, SECONDS
1/h² x10⁻⁶, CENTIMETERS⁻²
0
50
100
150
200
250
300
350
1
2
3
4
5
6
7
8
9
10
11

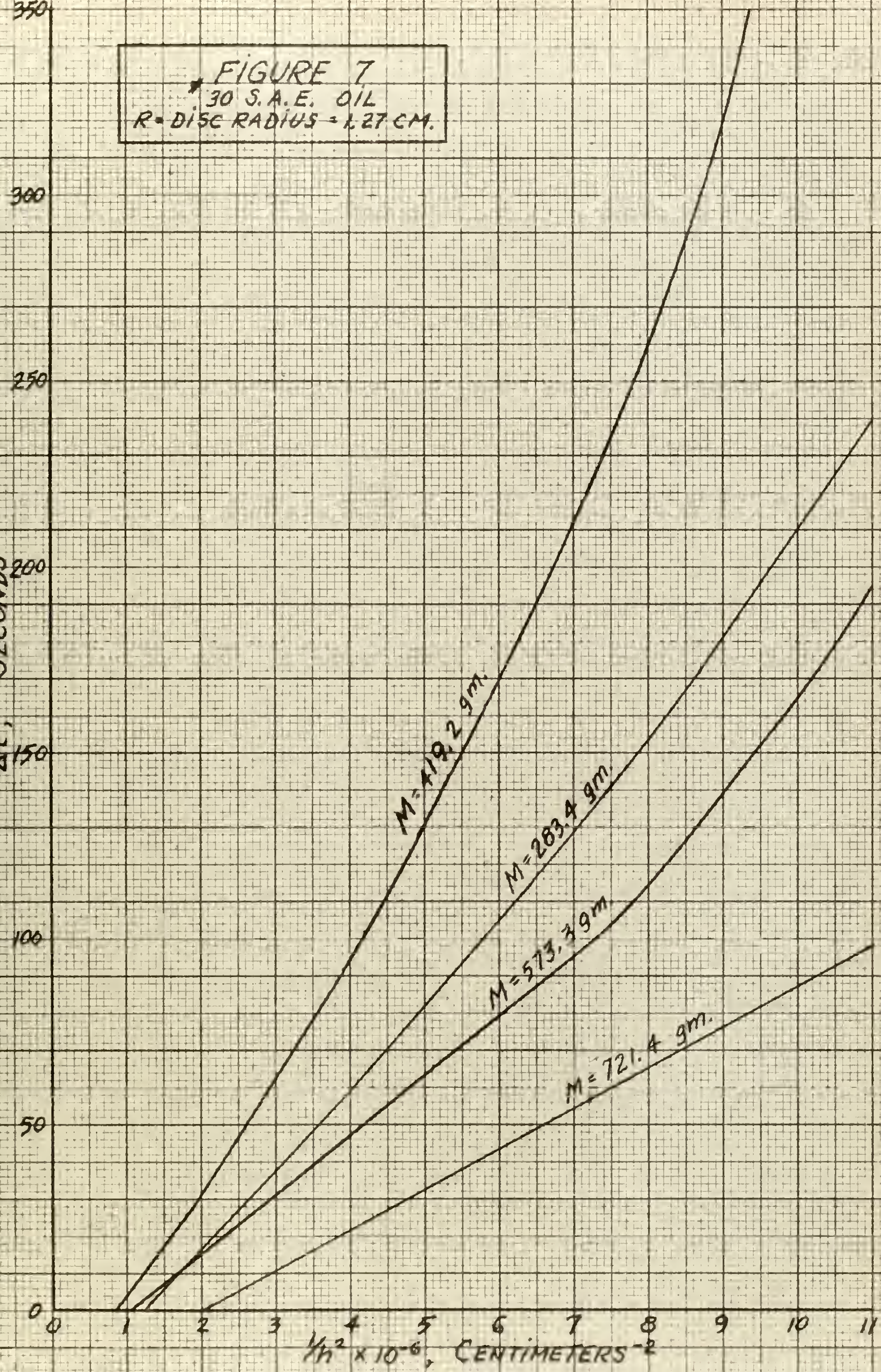
FIGURE 7
30 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
M = 419.2 gm.
M = 283.4 gm.
M = 573.79 gm.
M = 721.4 gm.
Δt, SECONDS
1/h² x 10⁻⁶, CENTIMETERS⁻²
0
50
100
150
200
250
300
350
1
2
3
4
5
6
7
8
9
10
11

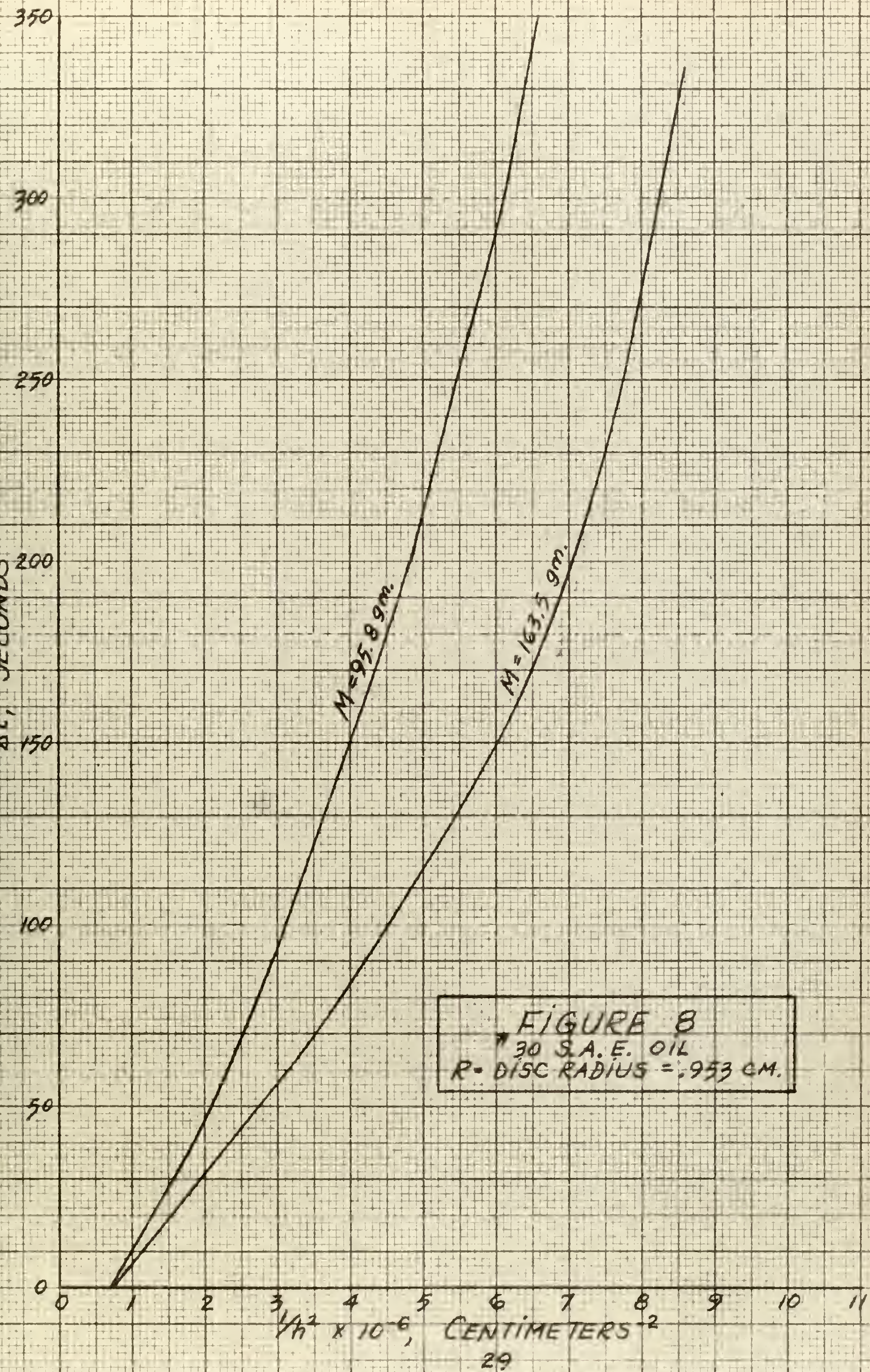

FIGURE 8
30 S.A.E. OIL
R= DISC RADIUS = .953 CM.

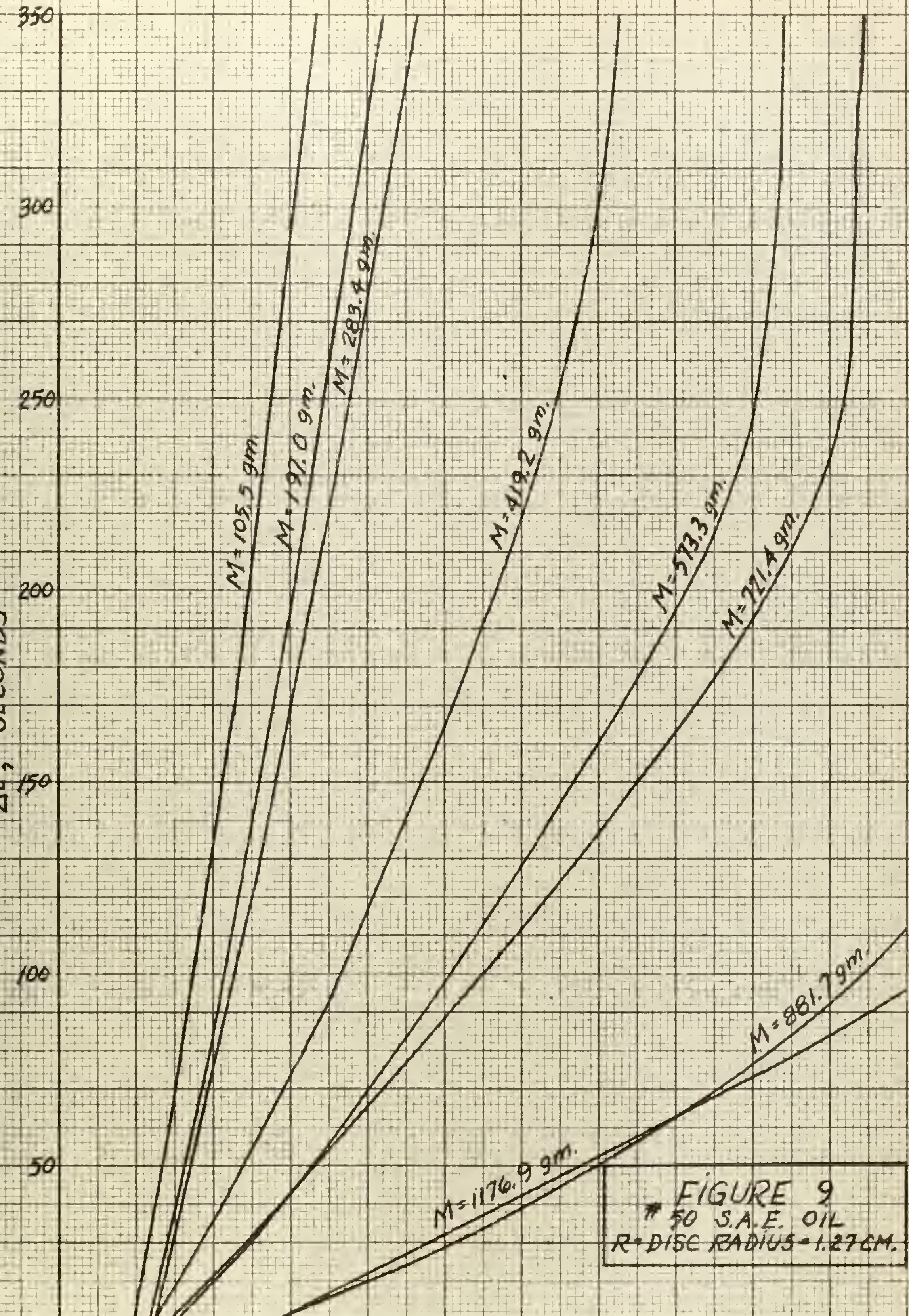

FIGURE 9
# 50 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
M = 105.5 gm.
M = 197.0 gm.
M = 283.4 gm.
M = 419.2 gm.
M = 573.3 gm.
M = 721.4 gm.
M = 881.7 gm.
M = 1176.9 gm.
Δt, SECONDS
1/h² x10⁻⁶, CENTIMETERS⁻²
0
50
100
150
200
250
300
350
1
2
3
4
5
6
7
8
9
10
11

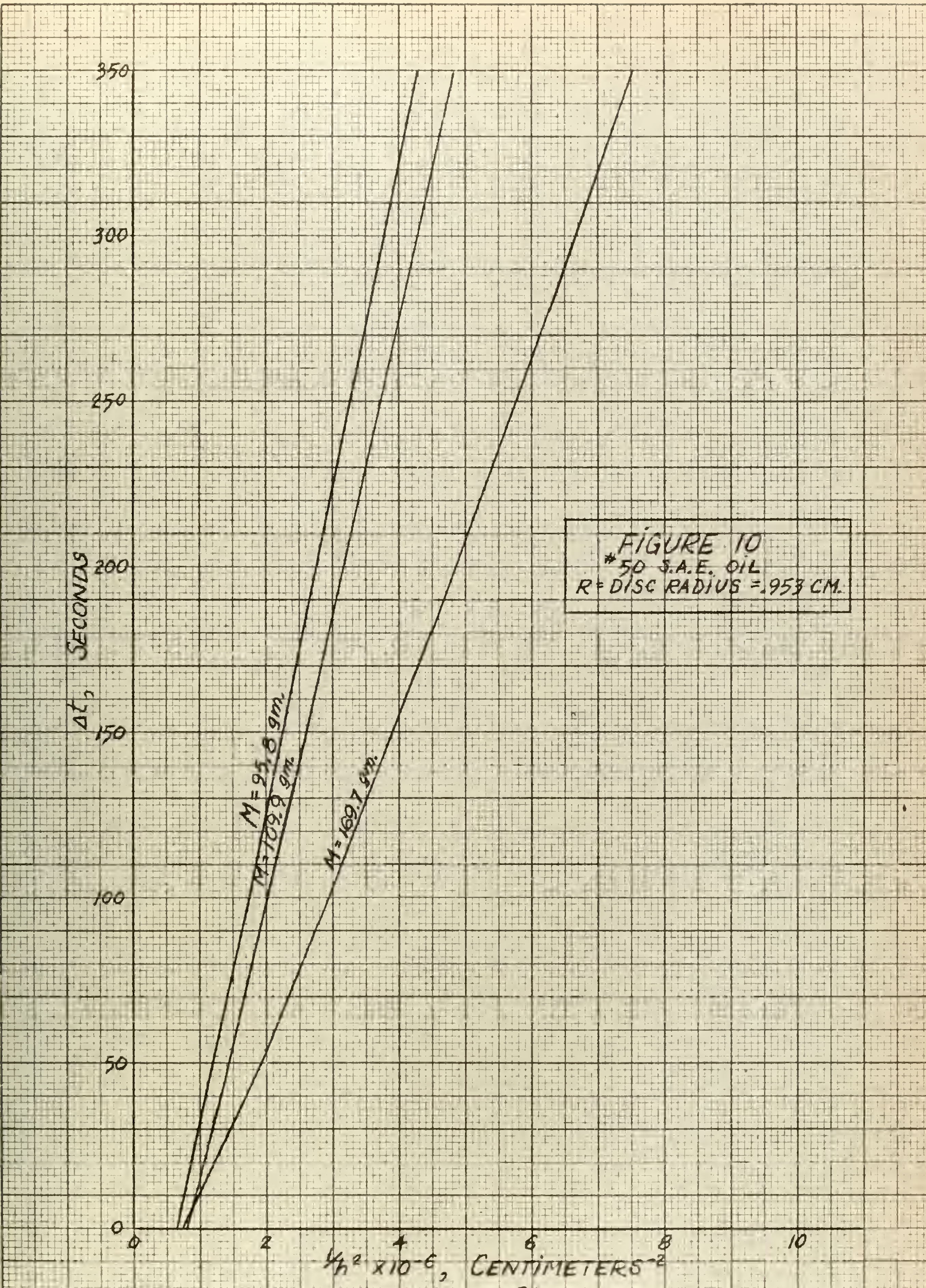
FIGURE 10
#50 S.A.E. OIL
R = DISC RADIUS = .953 CM.
M = 95.8 gm.
M = 109.9 gm.
M = 169.7 gm.
Δt, SECONDS
350
300
250
200
150
100
50
0
0
2
4
6
8
10
1/h² x10⁻⁶, CENTIMETERS⁻²

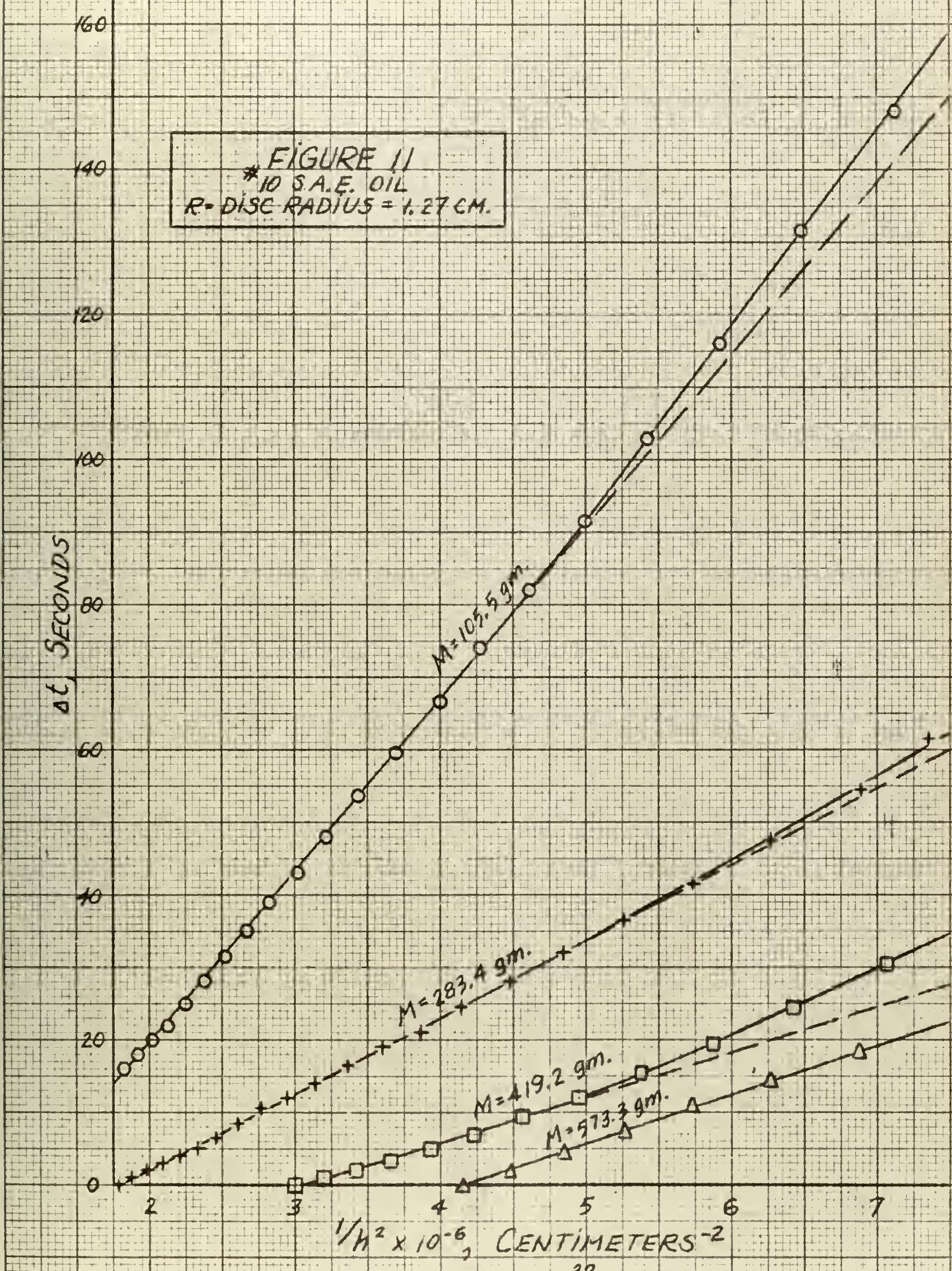

FIGURE 11
*10 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
160
140
120
100
80
60
40
20
0
Δt, SECONDS
M = 105.5 gm.
M = 283.4 gm.
M = 419.2 gm.
M = 573.3 gm.
2
3
4
5
6
7
1/h² x 10⁻⁶, CENTIMETERS⁻²

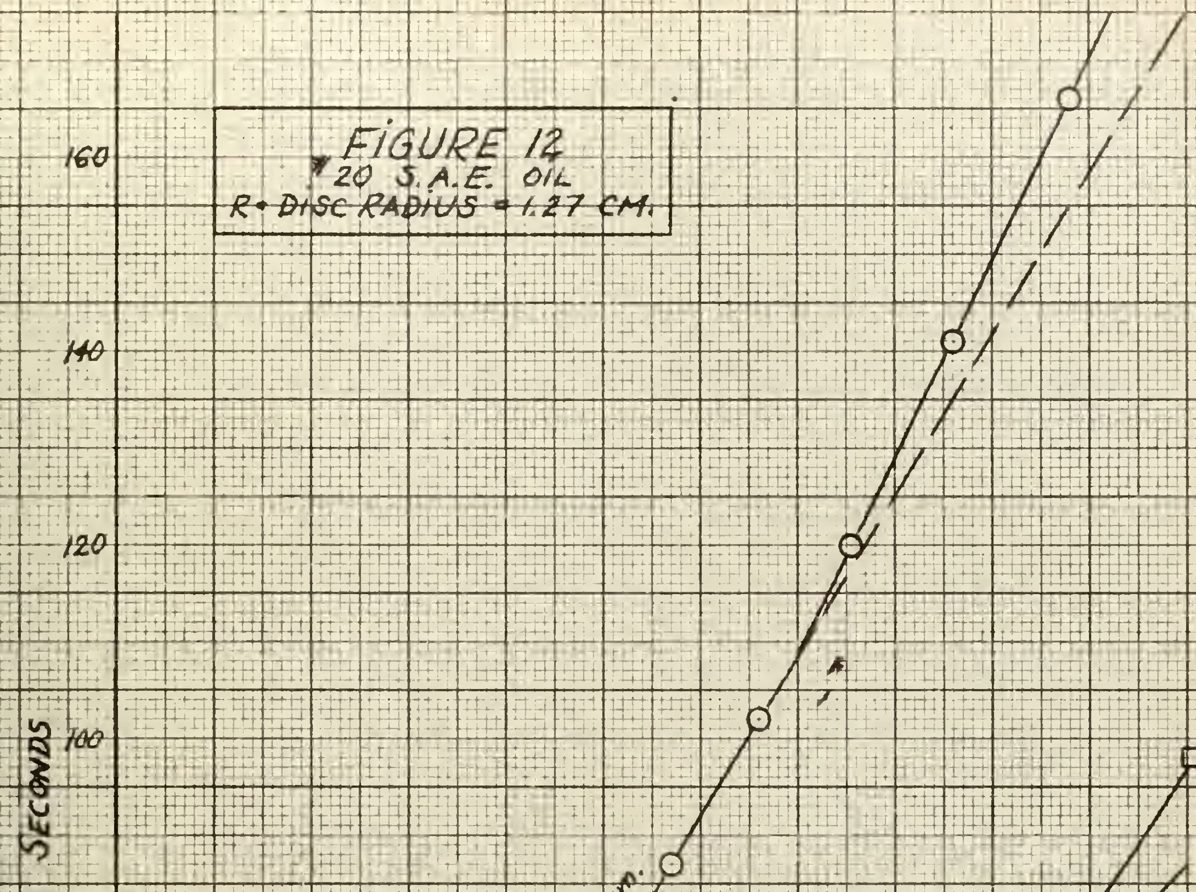
FIGURE 12
#20 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
160
140
120
100
80
60
40
20
0
Δt, SECONDS
M=105.5 gm.
M=197.0 gm.
1.6
2.0
2.5
3.0
3.5
1/h² x 10⁻⁶, CENTIMETERS⁻²

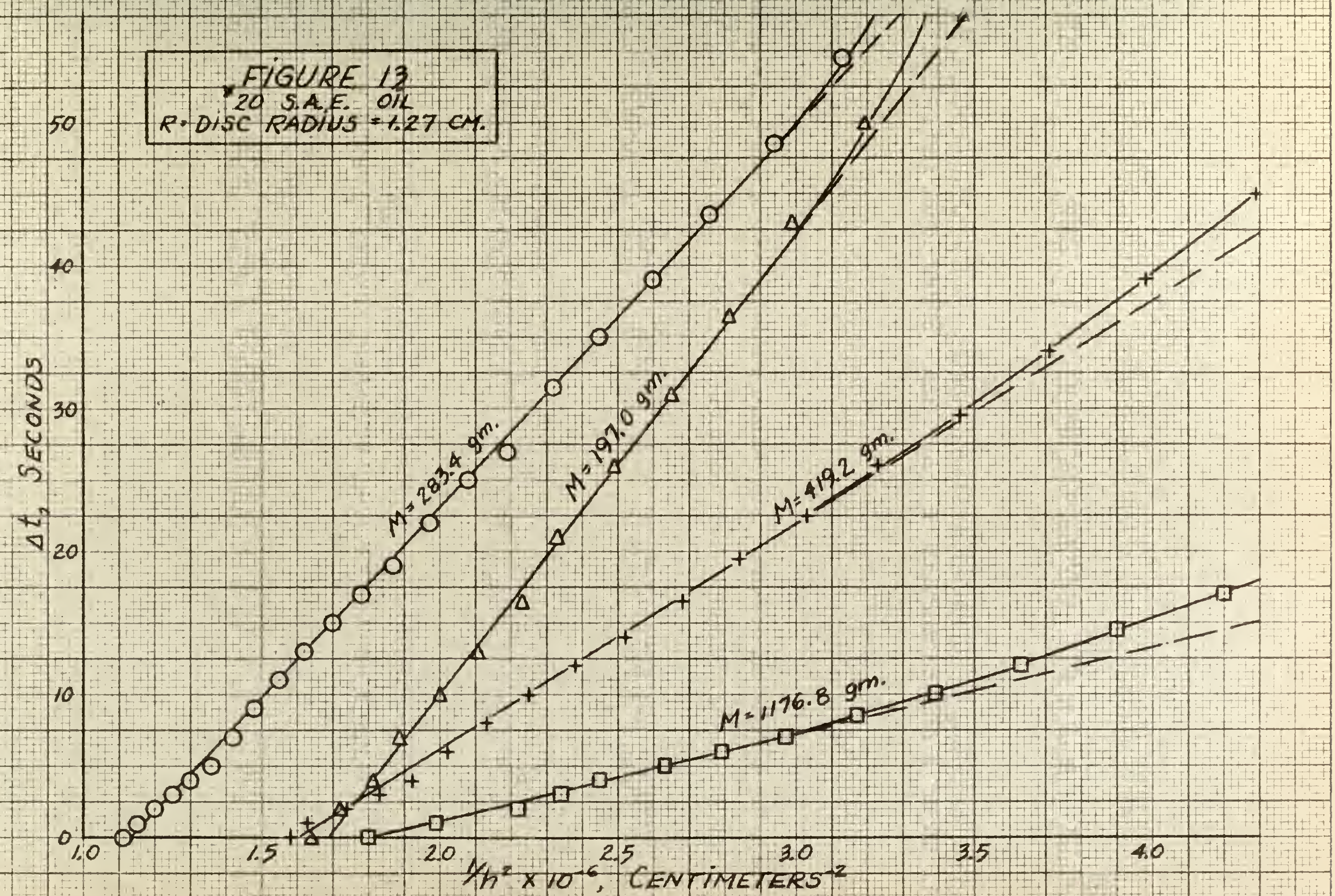

FIGURE 13
*20 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
M = 283.4 gm.
M = 197.0 gm.
M = 419.2 gm.
M = 1176.8 gm.
Δt, SECONDS
0
10
20
30
40
50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
1/h² x 10⁻⁶, CENTIMETERS⁻²

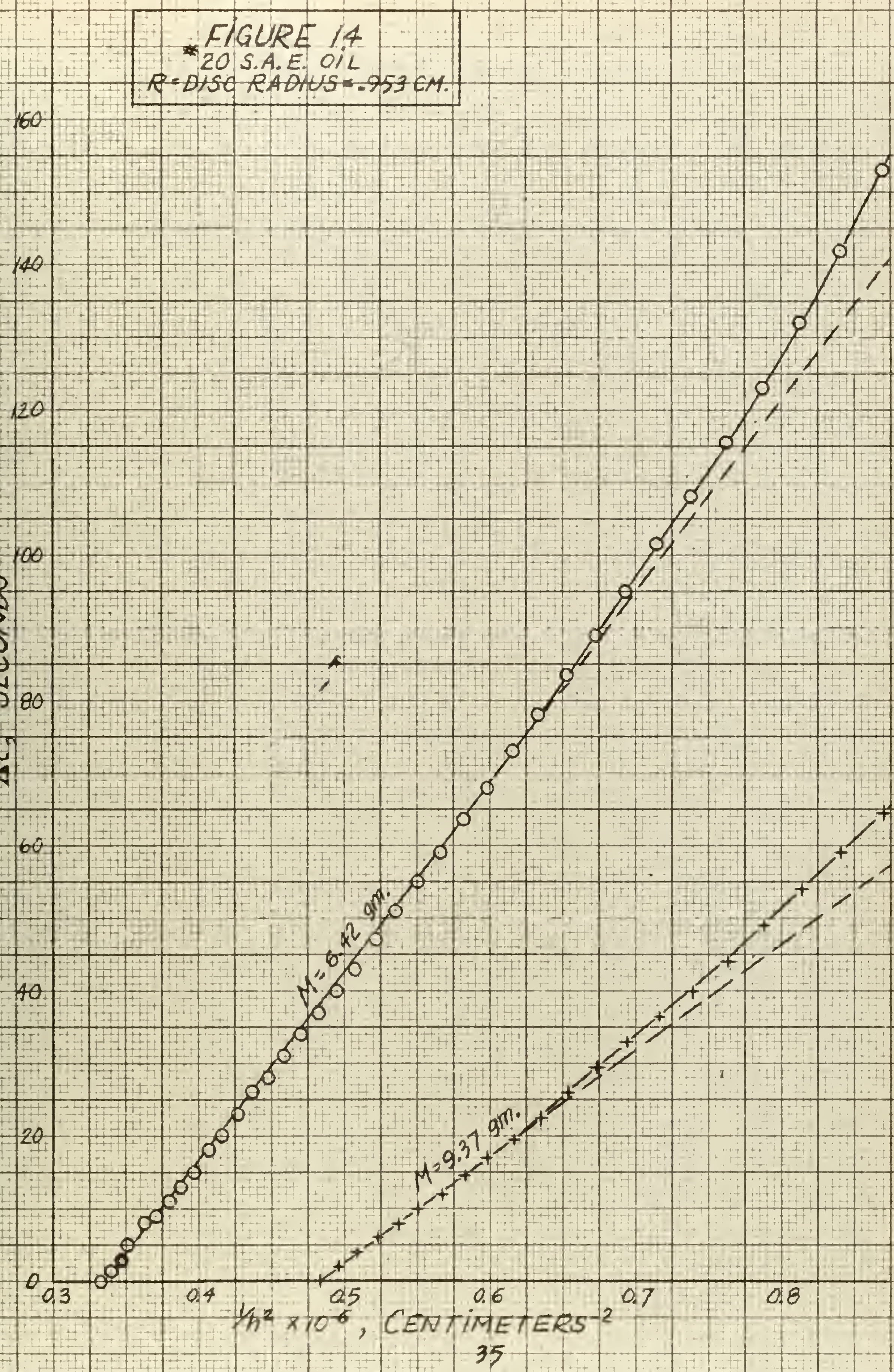

*FIGURE 14
20 S.A.E. OIL
R = DISC RADIUS = .953 CM.
Δt, SECONDS
1/h² x10⁻⁶, CENTIMETERS⁻²
M = 8.42 gm.
M = 9.37 gm.
0
20
40
60
80
100
120
140
160
0.3
0.4
0.5
0.6
0.7
0.8

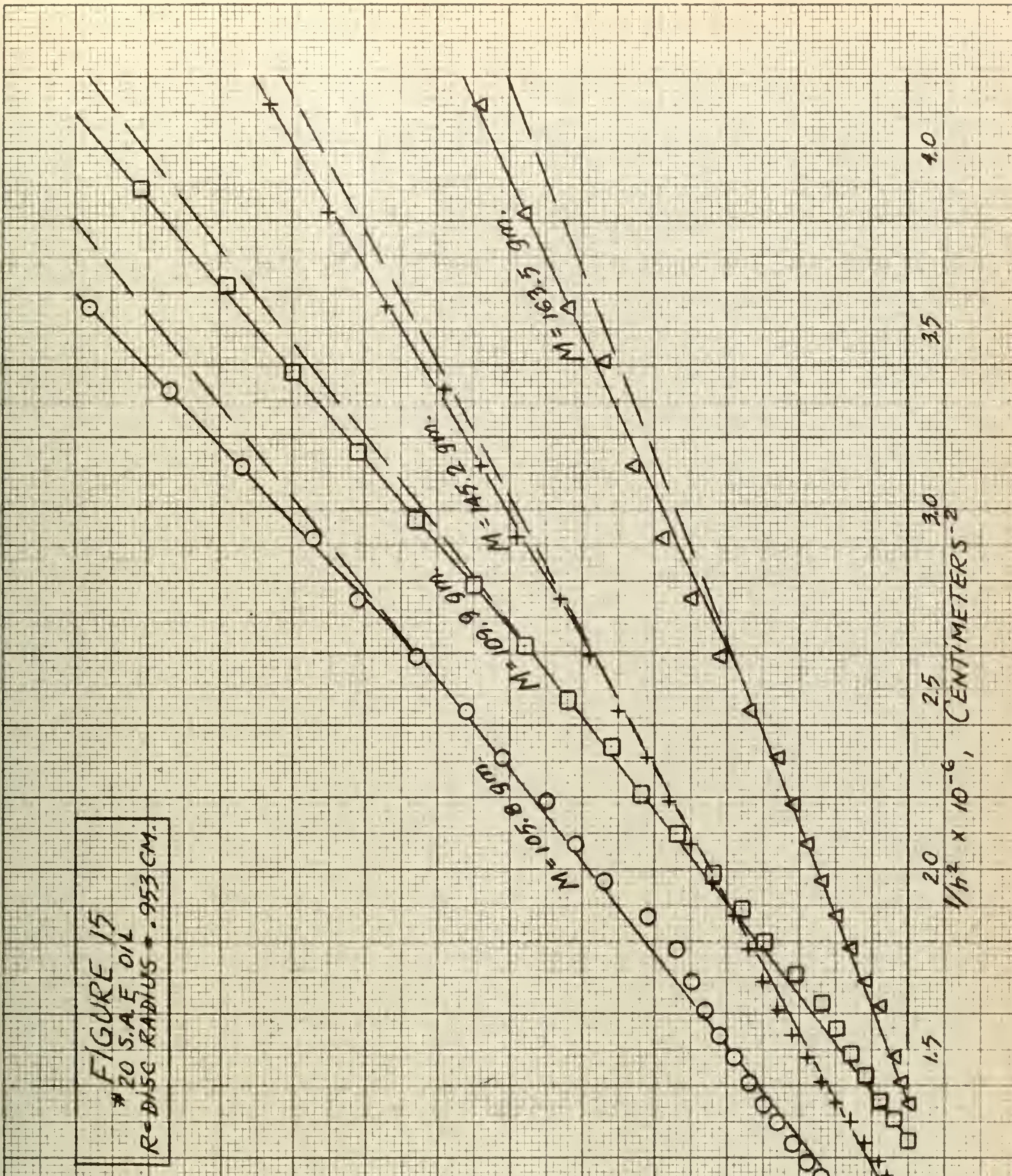
FIGURE 15
#20 S.A.E. OIL
R = DISC RADIUS = .953 CM.
M = 105.8 gm.
M = 109.9 gm.
M = 145.2 gm.
M = 163.5 gm.
Δt, SECONDS
1/h² × 10⁻⁶, CENTIMETERS⁻²
0
10
20
30
40
50
1.0
1.5
2.0
2.5
3.0
3.5
4.0

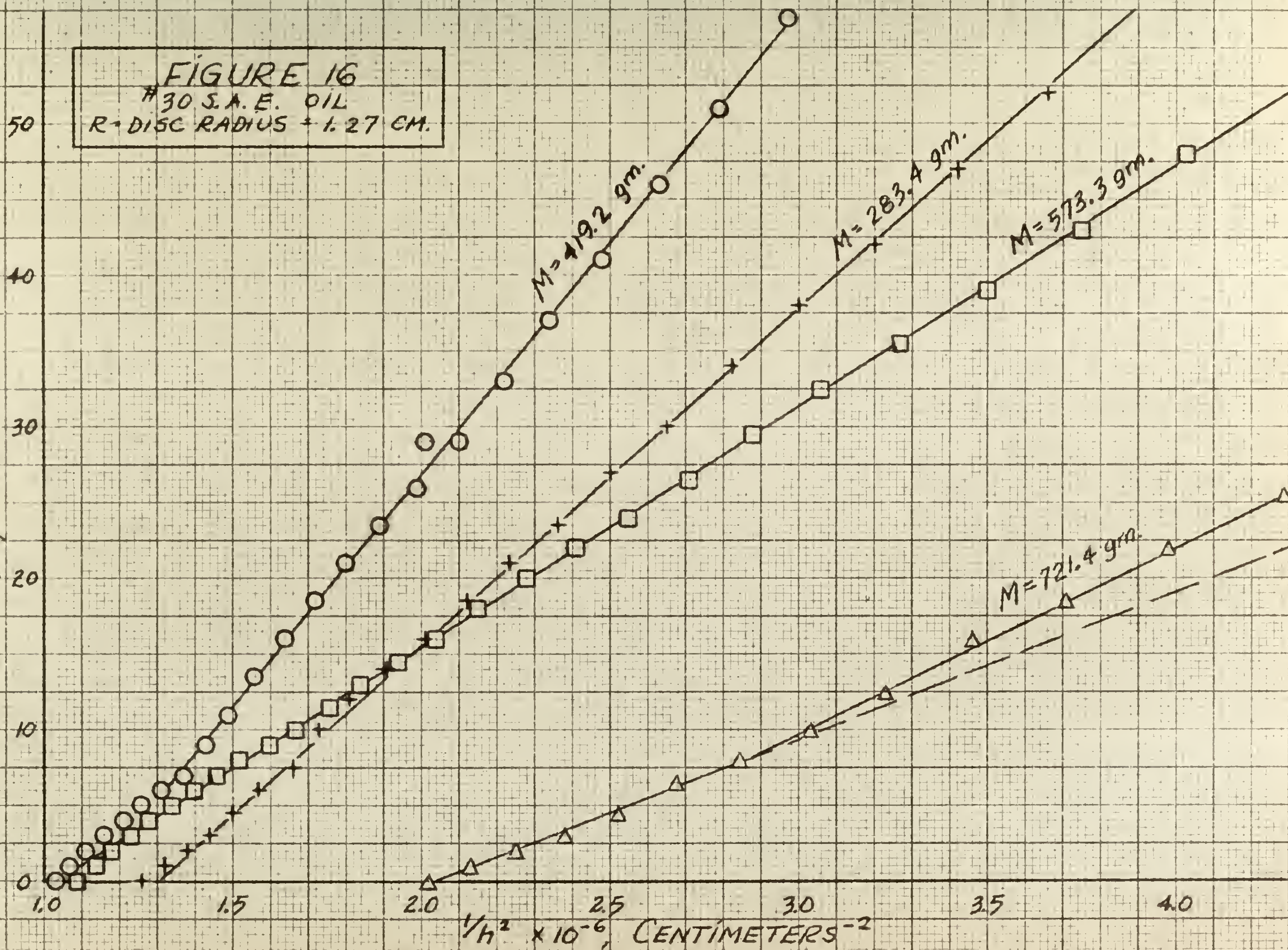
FIGURE 16
#30 S.A.E. OIL
R - DISC RADIUS = 1.27 CM.
M = 419.2 gm.
M = 283.4 gm.
M = 573.3 gm.
M = 721.4 gm.
Δt, SECONDS
0
10
20
30
40
50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
1/h² × 10⁻⁶, CENTIMETERS⁻²

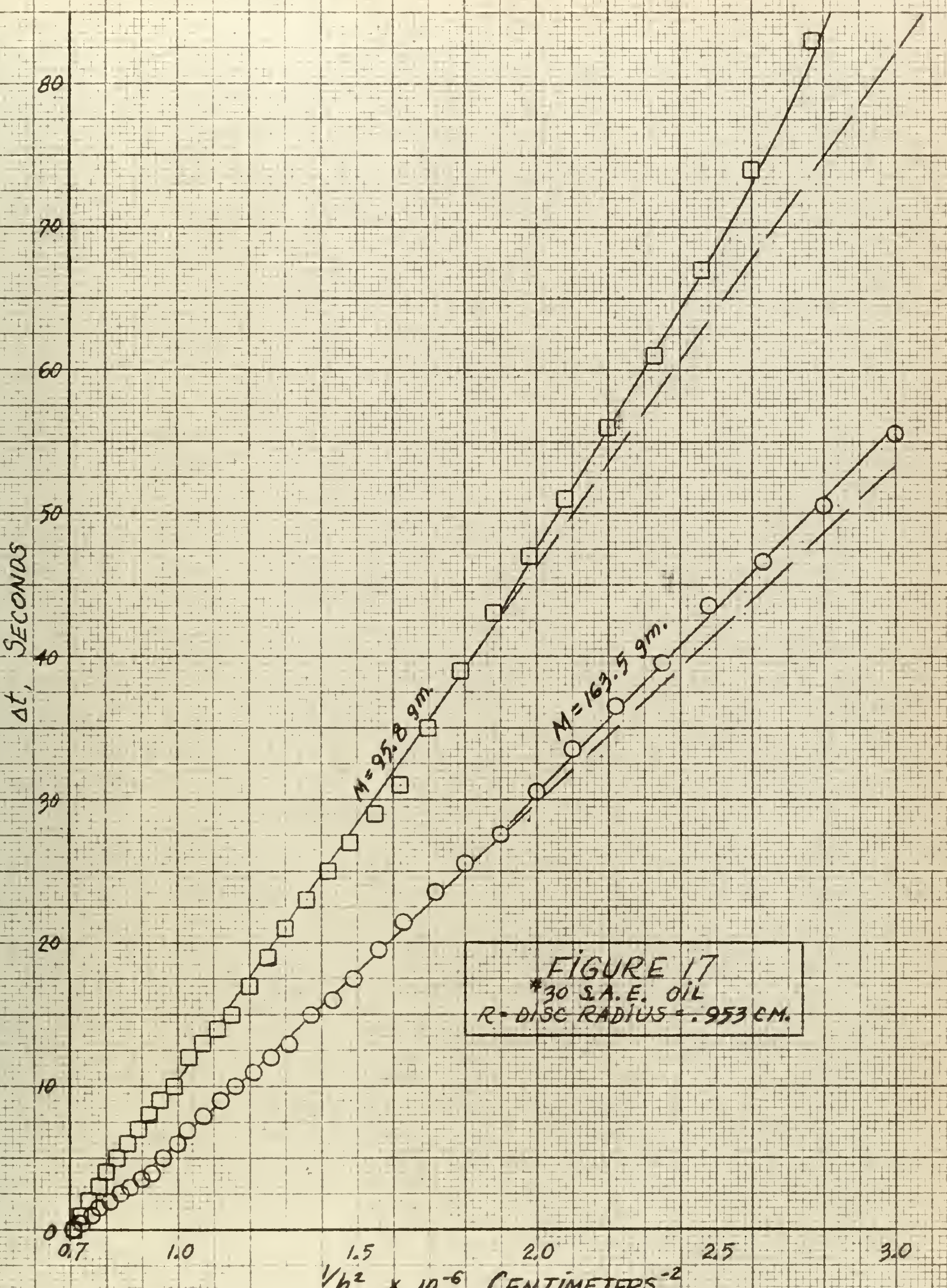

FIGURE 17
*30 S.A.E. OIL
R = DISC RADIUS = .953 CM.
M = 95.8 gm.
M = 163.5 gm.
Δt, SECONDS
1/h² x 10⁻⁶, CENTIMETERS⁻²
0
10
20
30
40
50
60
70
80
0.7
1.0
1.5
2.0
2.5
3.0

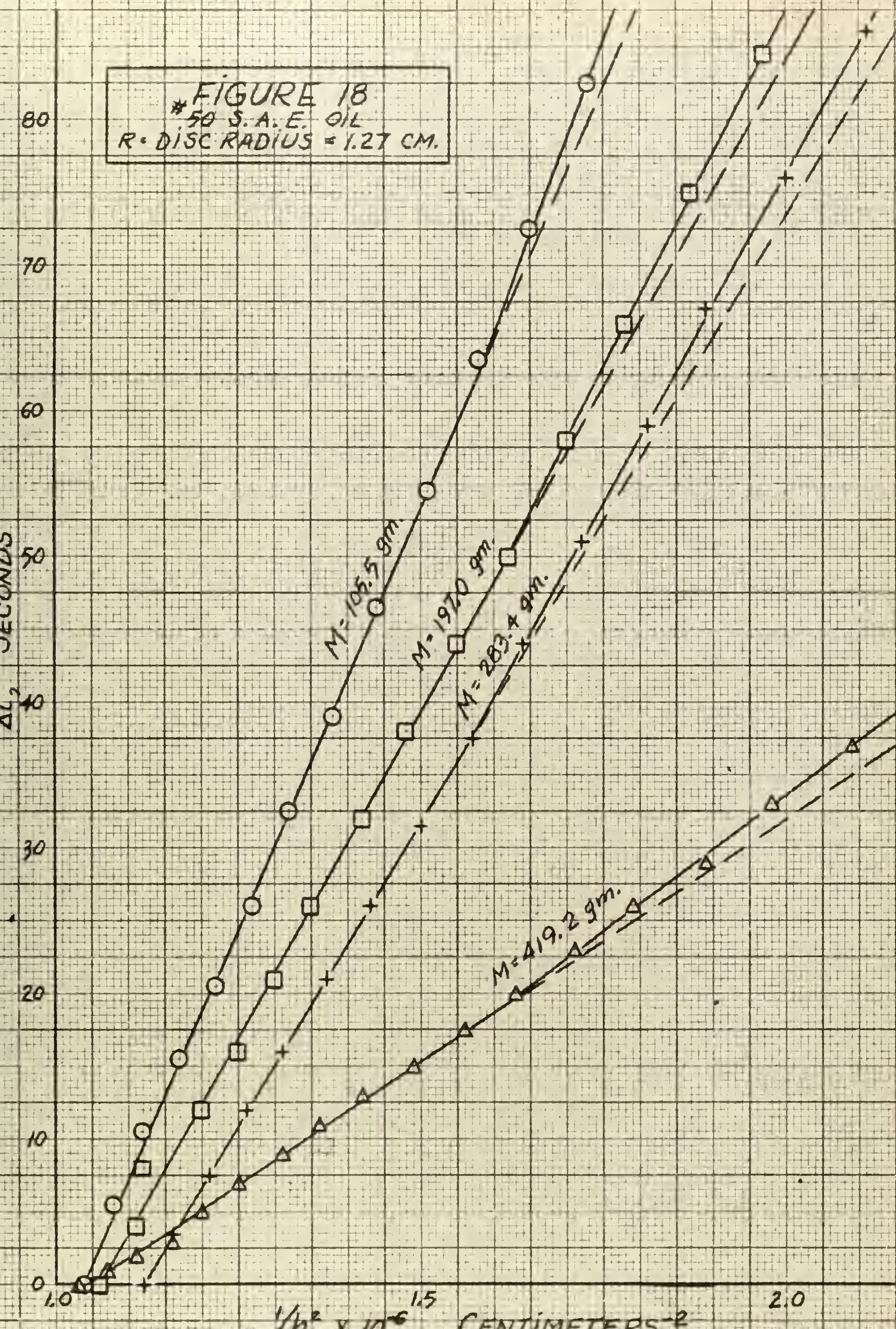
FIGURE 18
*50 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
M = 105.5 gm.
M = 197.0 gm.
M = 283.4 gm.
M = 419.2 gm.
Δt_2 SECONDS
$1/h^2 \times 10^{-6}$, CENTIMETERS^{-2}
0
10
20
30
40
50
60
70
80
1.0
1.5
2.0

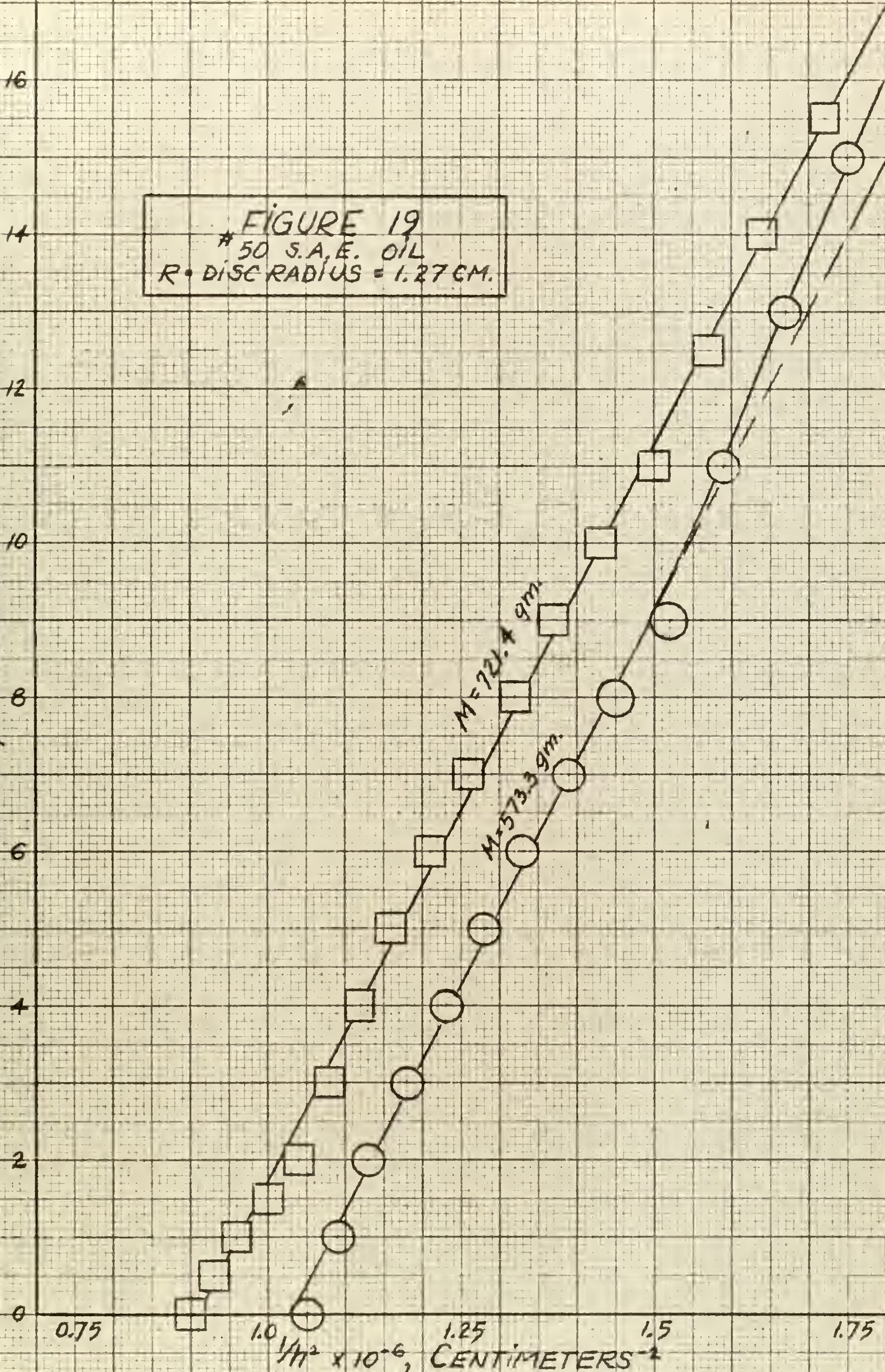
FIGURE 19
#50 S.A.E. OIL
R = DISC RADIUS = 1.27 CM.
M=721.4 gm.
M=573.3 gm.
Δt, SECONDS
16
14
12
10
8
6
4
2
0
0.75
1.0
1.25
1.5
1.75
1/h² x 10⁻⁶, CENTIMETERS⁻²

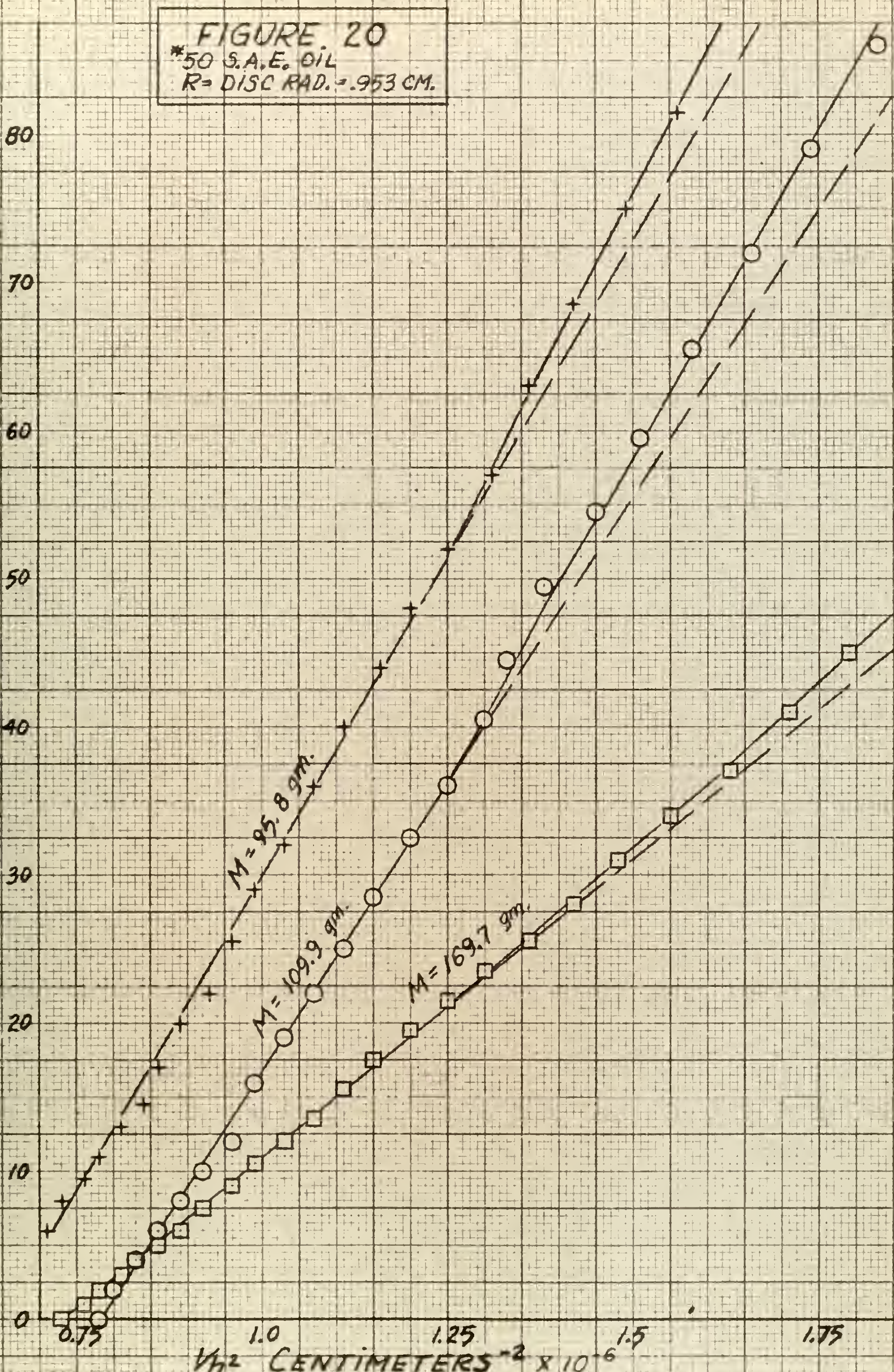
FIGURE 20
*50 S.A.E. OIL
R= DISC RAD. = .953 CM.
M = 95.8 gm.
M = 109.9 gm.
M = 169.7 gm.
Δt, SECONDS
0
10
20
30
40
50
60
70
80
0.75
1.0
1.25
1.5
1.75
1/h², CENTIMETERS⁻² x 10⁻⁶

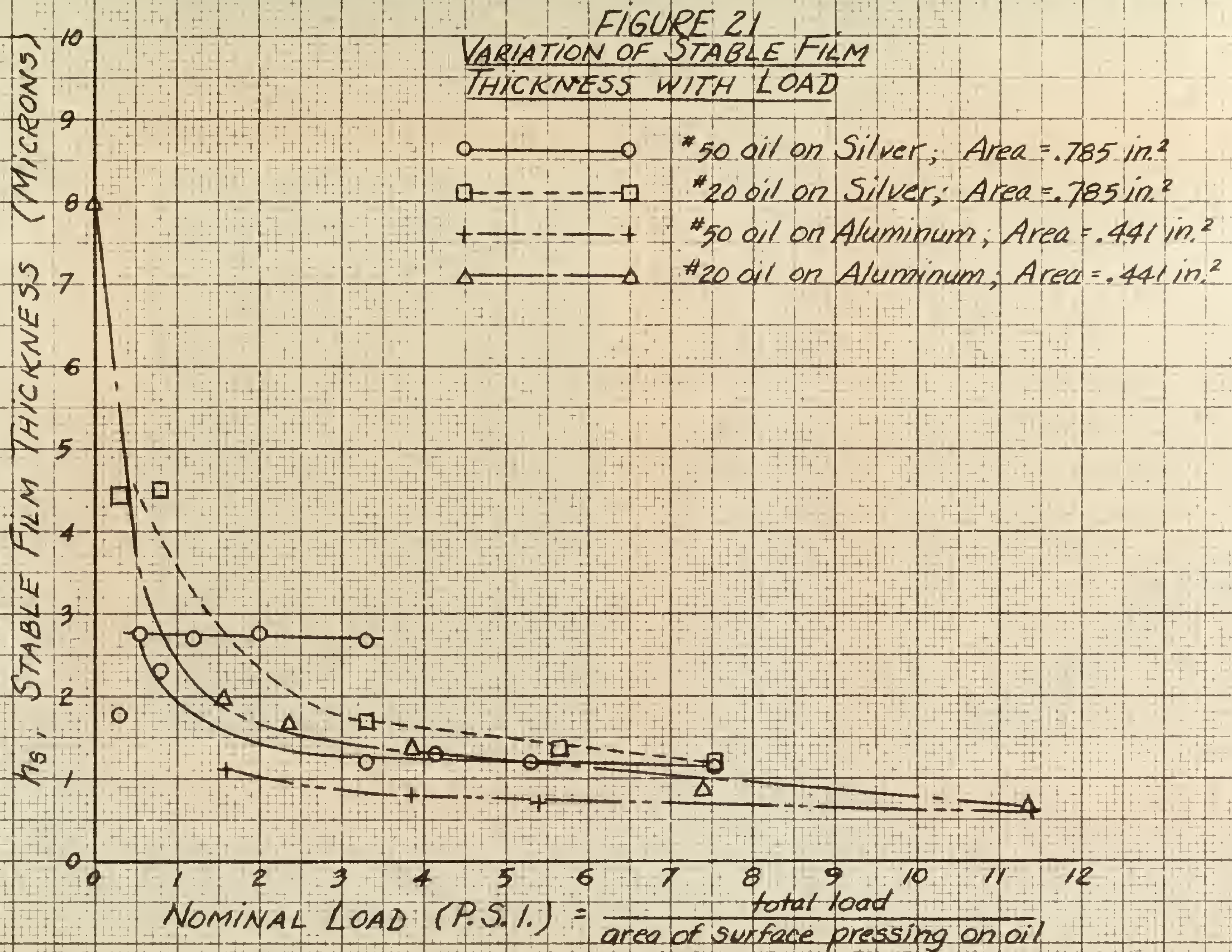

FIGURE 21
VARIATION OF STABLE FILM THICKNESS WITH LOAD

Figure 22. Photomicrograph (100 x) of silver mirrors upon completion of experiments. Dark areas are glass. Lightly shaded areas are not on the silver surface, but are due to imperfections in the photographic plate emulsion.

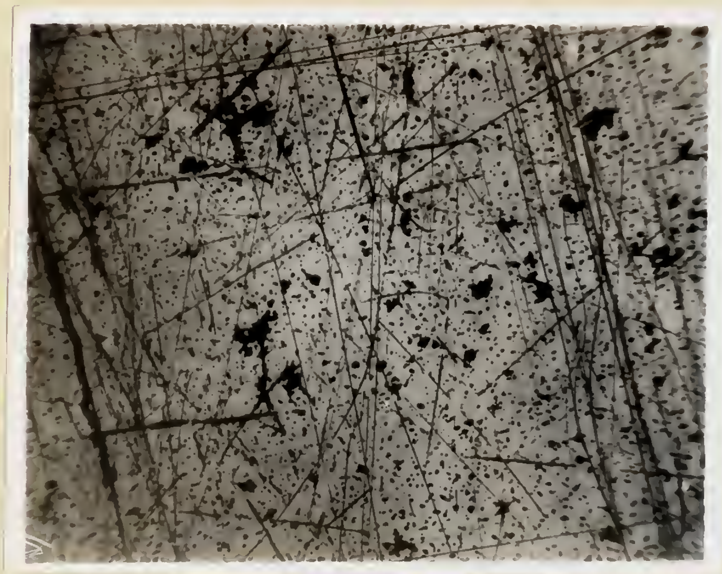

Figure 23. Photomicrograph (100 x) of aluminum mirror upon completion of experiments. Dark areas are glass.

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APPENDIX I

PROPERTIES OF LUBRICATING OILS

Oil, S. A. E. Number	Temperature, Degrees F.	Viscosity, Centistokes	Index of Refraction
10	73.4 (23 C.)	-	1.4866
	100	34.13	-
	210	5.42	-
20	73.4 (23 C.)	-	1.4870
	100	74.0	-
	210	8.74	-
30	73.4 (23 C.)	-	1.4870
	100	114.1	-
	210	11.28	-
50	73.4 (23 C.)	-	1.4900
	100	240.1	-
	210	18.12	-

Note: No additives in any of the oil samples. Number 10 S. A. E. Oil was centrifuged for 30 minutes at 10 g.

Supplier: Shell Developement Company, Emeryville, Research Center, California.

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #10 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22 C.
Mass of Load: 105.5 gm.

n = fringe order
N = total number of fringes between Mercury blue and green lines

h (microns)	$(1/h^2) \times 10^{-6}$ (cm.$^{-2}$)	t (sec.)	n	N
9.600	1.09	0	0	
9.418	1.13	1	1	
9.235	1.17	2	2	
9.052	1.22	3	3	
8.869	1.27	4	4	
8.686	1.33	5	5	
8.503	1.38	6	6	
8.320	1.45	7	7	
8.137	1.51	8.5	8	
7.954	1.58	10	9	
7.771	1.66	12	10	
7.588	1.74	14	11	
7.405	1.82	16	12	
7.222	1.92	18	13	
7.039	2.02	20	14	
6.856	2.13	22	15	
6.673	2.25	25	16	
6.490	2.38	28	17	
6.307	2.52	31.5	18	
6.124	2.67	35	19	
5.941	2.83	39	20	
5.758	3.02	43	21	
5.575	3.22	48	22	
5.392	3.44	53.5	23	
5.209	3.69	59.5	24	
5.026	4.00	66.5	25	
4.843	4.27	74	26	
4.660	4.61	82	27	
4.477	4.99	91.5	28	
4.294	5.43	103	29	
4.111	5.92	116	30	
3.928	6.48	131.5	31	
3.745	7.13	148	32	
3.562	7.88	170	33	
3.379	8.76	197	34	
3.196	9.79	234	35	
3.013	11.02	286.5	36	
2.921	11.72	327	36.5	
2.830	12.49	428	37	3.9

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #10 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22.7 C.
Mass of Load: 283.4 gm.

n = fringe order
N = total number of fringes between Mercury blue and green lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
7.471	1.79	0	0	
7.288	1.88	1	1	
7.105	1.98	2	2	
6.922	2.09	3	3	
6.739	2.21	4	4	
6.556	2.33	5	5	
6.373	2.46	6.5	6	
6.190	2.61	8.5	7	
6.007	2.77	10.5	8	
5.824	2.95	12	9	
5.641	3.14	14	10	
5.458	3.36	16.5	11	
5.275	3.59	19	12	
5.092	3.86	21	13	
4.909	4.15	24.5	14	
4.726	4.48	28	15	
4.543	4.85	32	16	
4.360	5.26	36.5	17	
4.177	5.73	41.5	18	
3.994	6.27	47.5	19	
3.811	6.89	54.5	20	
3.628	7.60	61.5	21	
3.445	8.43	71.5	22	
3.262	9.40	82.5	23	
3.079	10.55	96.5	24	
2.896	11.96	112	25	
2.713	13.59	140	26	
2.621	14.56	173.5	26.5	
2.576	15.08	286	26.75	3.55

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #10 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23.4 C.
Mass of Load: 419.2 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
5.776	3.00	0	0	
5.593	3.20	1	1	
5.410	3.42	2	2	
5.227	3.66	3.5	3	
5.044	3.93	5	4	
4.861	4.23	7	5	
4.678	4.56	9.5	6	
4.495	4.95	12	7	
4.312	5.38	15.5	8	
4.129	5.87	19.5	9	
3.946	6.42	24.5	10	
3.763	7.06	30.5	11	
3.580	7.80	37.5	12	
3.397	8.66	47.5	13	
3.214	9.68	60	14	
3.123	10.25	68.5	14.5	
3.031	10.88	79	15	
2.940	11.57	92.5	15.5	
2.848	12.33	113	16	
2.757	13.16	197	16.5	3.8

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #10 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22.6 C.
Mass of Load: 573.3 gm.

n = fringe order
N = number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ (cm.$^{-2}$)	t (sec.)	n	N
4.909	4.15	0	0	
4.726	4.48	2	1	
4.543	4.85	4.5	2	
4.360	5.26	7.5	3	
4.177	5.73	11	4	
3.994	6.27	14.5	5	
3.811	6.88	18.5	6	
3.628	7.60	22.5	7	
3.445	8.43	28.5	8	
3.262	9.40	34.5	9	
3.079	10.55	42.5	10	
2.896	11.92	53	11	
2.805	12.71	61.5	11.5	
2.713	13.58	71	12	
2.622	14.55	89.5	12.5	
2.539	15.51	316.5	12.95	3.5

Oil: #20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF

Ambient Temperature: 23.5 C.
Mass of Load: 105.5 gm.

7.691	1.69	0	0	
7.507	1.78	7	1	
7.323	1.87	14	2	
7.140	1.96	22	3	
6.956	2.07	30.5	4	
6.773	2.18	40	5	
6.589	2.30	50	6	
6.405	2.44	60.5	7	
6.222	2.58	73	8	
6.038	2.74	87	9	
5.855	2.92	102	10	
5.671	3.11	120	11	
5.487	3.32	141	12	
5.304	3.56	166	13	
5.120	3.82	198	14	
4.937	4.11	241	15	
4.753	4.43	315	16	
4.661	4.60	389	16.5	
4.569	4.79	533	17	6.3

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23.5 C.
Mass of Load: 1157.8 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ (cm.$^{-2}$)	t (sec.)	n	N
6.777	2.18	0	0	
6.594	2.30	6	1	
6.410	2.43	13.5	2	
6.226	2.58	21	3	
6.043	2.74	29	4	
5.859	2.91	39	5	
5.676	3.11	50	6	
5.492	3.32	62	7	
5.308	3.55	78	8	
5.125	3.81	98	9	
4.758	4.42	157	11	
4.574	4.78	206	12	
4.390	5.19	230	13	
4.207	5.65	312	14	5.8
3.917	6.52	463		5.4

Oil: # 20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22.5 C.
Mass of Load: 197.0 gm.

7.802	1.64	0	0	
7.618	1.72	2	1	
7.434	1.81	4	2	
7.251	1.90	7	3	
7.067	2.00	10	4	
6.884	2.11	13	5	
6.700	2.23	16.5	6	
6.516	2.36	21	7	
6.333	2.49	26	8	
6.149	2.65	31	9	
5.966	2.81	36.5	10	
5.782	2.99	43	11	
5.598	3.19	50	12	
5.415	3.41	60	13	
5.231	3.65	72	14	
5.048	3.93	91	15	
4.864	4.23	126	16	
4.680	4.57	231	17	
4.589	4.75	492	17.5	
4.497	4.95	1415	18	6.2

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23.4 C.
Mass of Load: 283.4 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ (cm.$^{-2}$)	t (sec.)	n	N
9.507	1.11	0	0	
9.324	1.15	1	1	
9.140	1.20	2	2	
8.957	1.25	3	3	
8.773	1.30	4	4	
8.589	1.36	5	5	
8.406	1.42	7	6	
8.222	1.48	9	7	
8.039	1.55	11	8	
7.855	1.62	13	9	
7.671	1.70	15	10	
7.488	1.78	17	11	
7.304	1.87	19	12	
7.121	1.97	22	13	
6.937	2.08	25	14	
6.753	2.19	28	15	
6.570	2.32	31.5	16	
6.386	2.45	35	17	
6.203	2.60	39	18	
6.019	2.76	43.5	19	
5.835	2.94	48.5	20	
5.652	3.13	54.5	21	
5.468	3.35	61.5	22	
5.285	3.58	69.5	23	
5.101	3.84	78.5	24	
5.009	3.99	82.5	24.5	
4.917	4.14	89.5	25	
4.826	4.29	96.5	25.5	
4.734	4.46	108.5	26	
4.642	4.64	158.5	26.5	6.4
4.497	4.95	844.5		6.2

APPENDIX II
TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23 C.
Mass of Load: 283.4 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
10.007	1.00	0	0	
9.823	1.04	1	1	
9.640	1.08	2	2	
9.456	1.12	3	3	
9.272	1.16	4	4	
9.089	1.21	5	5	
8.905	1.26	6	6	
8.722	1.32	7	7	
8.538	1.37	8.5	8	
8.354	1.43	10	9	
8.171	1.50	12.5	10	
7.987	1.57	14.5	11	
7.804	1.64	16.5	12	
7.620	1.72	18.5	13	
7.436	1.81	20.5	14	
7.253	1.90	23	15	
7.069	2.00	25.5	16	
6.886	2.11	28	17	
6.702	2.23	30.5	18	
6.518	2.35	33.5	19	
6.335	2.49	37	20	
6.151	2.64	41	21	
5.968	2.81	45.5	22	
5.784	2.99	50	23	
5.600	3.19	56	24	
5.417	3.41	63	25	
5.325	3.53	70	25.5	
5.233	3.65	79	26	
5.141	3.78	102	26.5	
5.105	3.84		26.7	6.9

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22.5 C.
Mass of Load: 419.2 gm.

n = fringe order
N = total number of ringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
7.948	1.58	0	0	
7.765	1.63	1	1	
7.581	1.74	2	2	
7.398	1.83	3	3	
7.214	1.92	4	4	
7.031	2.02	6	5	
6.847	2.13	8	6	
6.664	2.25	10	7	
6.480	2.38	12	8	
6.297	2.52	14	9	
6.113	2.68	16.5	10	
5.929	2.84	19.5	11	
5.746	3.03	22.5	12	
5.562	3.23	26	13	
5.379	3.46	29.5	14	
5.195	3.71	34	15	
5.011	3.98	39	16	
4.828	4.29	45	17	
4.736	4.46	49.5	17.5	
4.644	4.64	56	18	
4.552	4.83	69	18.5	
4.461	5.03	123	18.9	6.15

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23.7 C.
Mass of Load: 1176.8 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
7.453	1.80	0	0	
7.086	1.99	1	2	
6.718	2.22	2	4	
6.535	2.34	3	5	
6.351	2.48	4	6	
6.168	2.63	5	7	
5.984	2.79	6	8	
5.800	2.97	7	9	
5.617	3.17	8.5	10	
5.433	3.39	10	11	
5.250	3.63	12	12	
5.066	3.90	14.5	13	
4.882	4.20	17	14	
4.699	4.53	20	15	
4.515	4.91	24	16	
4.332	5.33	28.5	17	
4.148	5.81	34	18	
3.964	6.36	41.5	19	
3.781	7.01	51.5	20	
3.597	7.73	68	21	
3.414	8.58	90	21.5	
3.230	9.59	158	22	
3.046	10.78	3278	23	4.2

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E. Ambient Temperature: 23.0 C.
Mirror Radius: .953 cm. Mass of Load: 6.42 gm.
Mirror Coating: Aluminum

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
17.333	0.33	0	0	
17.149	0.34	1.5	1	
16.966	0.35	3	2	
16.782	0.35	5	3	
16.598	0.36	8	4	
16.415	0.37	9	5	
16.231	0.38	11	6	
16.048	0.39	13	7	
15.864	0.40	15	8	
15.680	0.41	18	9	
15.497	0.42	20	10	
15.313	0.43	23	11	
15.130	0.44	26	12	
14.946	0.45	28	13	
14.762	0.46	31	14	
14.579	0.47	34	15	
14.395	0.48	37	16	
14.212	0.50	40	17	
14.028	0.51	43	18	
13.844	0.52	47	19	
13.661	0.54	51	20	
13.477	0.55	55	21	
13.294	0.57	59	22	
13.110	0.58	63.5	23	
12.926	0.60	68	24	
12.743	0.62	73	25	
12.559	0.63	78	26	
12.376	0.65	83.5	27	
12.192	0.67	89	28	
12.008	0.69	95	29	
11.825	0.72	101.5	30	
11.641	0.74	108	31	
11.458	0.76	115.5	32	
11.274	0.79	123	33	
11.090	0.81	132	34	
10.907	0.84	142	35	
10.723	0.87	153	36	
10.540	0.90	166.5	37	
10.356	0.93	184.5	38	
10.172	0.97	206	39	
9.989	1.00	230	40	
9.805	1.04	260	41	
9.622	1.08	293	42	
9.438	1.12	336	43	
9.254	1.17	388	44	
9.071	1.22	460	45	
8.887	1.27	539	46	
8.704	1.32	663	47	12

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E. Ambient Temperature: 22.9 C.

Mirror Radius: .953 cm. Mass of Load: 9.37 gm.

Mirror Coating: Aluminum

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
16.767	0.36	0	0	
16.583	0.36	1	1	
16.400	0.37	2	2	
16.217	0.38	3	3	
16.034	0.39	4	4	
15.851	0.40	5	5	
15.667	0.41	6	6	
15.484	0.42	7	7	
15.301	0.43	8	8	
15.118	0.44	9	9	
14.935	0.45	10	10	
14.751	0.46	11	11	
14.568	0.47	12	12	
14.385	0.48	13	13	
14.202	0.50	15	14	
14.019	0.51	17	15	
13.835	0.52	19	16	
13.652	0.54	21	17	
13.469	0.55	23	18	
13.284	0.57	25	19	
13.101	0.58	27.5	20	
12.917	0.60	30	21	
12.734	0.62	32.5	22	
12.551	0.64	35.5	23	
12.368	0.65	39	24	
12.185	0.67	42.5	25	
12.001	0.69	46	26	
11.818	0.72	49.5	27	
11.635	0.74	53	28	
11.451	0.76	57	29	
11.267	0.79	62	30	
11.084	0.81	67	31	
10.905	0.84	72	32	
10.722	0.87	77.5	33	
10.538	0.90	83	34	
10.354	0.93	90	35	
10.170	1.00	97	36	
9.986	1.00	104.5	37	
9.803	1.04	113	38	
9.619	1.08	122	39	
8.835	1.28	131	40	
8.652	1.34	142	41	
8.468	1.39	155	42	
8.285	1.46	169	43	
8.101	1.52	184	44	
7.997	1.56	201	45	
7.804	1.64	223.5	46	
7.620	1.72	244	47	
7.437	1.81	270.5	48	
7.253	1.90	302	49	10.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E. Ambient Temperature: 23.0 C.

Mirror Radius: .953 cm. Mass of Load: 105.8 gm.

Mirror Coating: Aluminum

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
10.805	0.86	0	0	
10.622	0.89	0.5	1	
10.438	0.92	1	2	
10.254	0.95	1.5	3	
10.071	0.99	2	4	
9.887	1.02	3	5	
9.704	1.06	4	6	
9.520	1.10	5	7	
9.336	1.15	6	8	
9.153	1.19	7	9	
8.969	1.24	8	10	
8.786	1.30	9	11	
8.602	1.35	10	12	
8.418	1.41	11	13	
8.235	1.48	12	14	
8.051	1.54	13	15	
7.868	1.61	14	16	
7.684	1.69	15	17	
7.500	1.78	16	18	
7.317	1.87	18	19	
7.133	1.97	21	20	
6.950	2.07	23	21	
6.766	2.19	25	22	
6.582	2.31	28	23	
6.399	2.44	30.5	24	
6.215	2.59	34	25	
6.032	2.75	38	26	
5.848	2.92	41	27	
5.664	3.12	46	28	
5.481	3.33	51	29	
5.297	3.56	56.5	30	
5.114	3.82	63	31	
4.930	4.12	70	32	
4.746	4.44	78	33	
4.563	4.80	87	34	
4.379	5.22	98	35	
4.196	5.68	111	36	
4.012	6.21	124	37	
3.828	6.82	142	38	
3.645	7.53	162	39	
3.461	8.35	186	40	
3.278	9.31	216	41	
3.094	10.45	248	42	
2.910	11.81	294	43	
2.727	13.45	346	44	
2.543	15.46	411	45	
2.360	17.96	506	46	
2.176	21.12	634	47	3.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: .953 cm.
Mirror Coating: Aluminum
Ambient Temperature: 23.1 C.
Mass of Load: 109.9 gm.

n = fringe order
N = total number of fringes between blue and green Mecury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
8.929	1.25	0	0	
8.745	1.31	1	1	
8.562	1.36	2	2	
8.378	1.43	3	3	
8.194	1.49	4	4	
8.011	1.56	5	5	
7.827	1.63	6	6	
7.644	1.71	8	7	
7.460	1.80	10	8	
7.276	1.89	11.5	9	
7.093	1.99	13.5	10	
6.909	2.10	16	11	
6.726	2.21	18.5	12	
6.542	2.34	20.5	13	
6.358	2.47	23.5	14	
6.175	2.62	26.5	15	
5.991	2.79	30	16	
5.808	2.97	34	17	
5.624	3.16	38	18	
5.440	3.38	42.5	19	
5.257	3.62	47	20	
5.073	3.89	53	21	
4.890	4.18	59	22	
4.706	4.52	66.5	23	
4.522	4.89	74.5	24	
4.339	5.31	85	25	
4.155	5.79	95.5	26	
3.972	6.34	107	27	
3.788	6.97	121.5	28	
3.604	7.70	140	29	
3.421	8.55	167	30	
3.237	9.54	204	31	
3.054	10.72	257	32	
2.870	12.14	347	33	
2.686	13.86	485	34	3.7

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: .953 cm.
Mirror Coating: Aluminum
Ambient Temperature: 23.1 C.
Mass of Load: 145.2 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
9.887	1.02	0	0	
9.704	1.06	0.5	1	
9.520	1.10	1	2	
9.336	1.15	1.5	3	
9.153	1.19	2	4	
8.969	1.24	3	5	
8.786	1.30	4	6	
8.602	1.35	5	7	
8.418	1.41	6	8	
8.235	1.48	7	9	
8.051	1.54	8	10	
7.868	1.61	9	11	
7.684	1.69	10	12	
7.500	1.78	11	13	
7.317	1.87	12	14	
7.133	1.97	13.5	15	
6.950	2.07	15	16	
6.766	2.19	16.5	17	
6.582	2.31	18	18	
6.399	2.44	20	19	
6.215	2.59	22	20	
6.032	2.75	24	21	
5.848	2.92	27	22	
5.664	3.12	29.5	23	
5.481	3.33	32	24	
5.297	3.56	26	25	
5.114	3.82	40	26	
4.930	4.12	44	27	
4.746	4.44	49	28	
4.563	4.80	55	29	
4.379	5.22	61	30	
4.200	5.68	68	31	
4.102	6.21	76	32	
3.828	6.82	86	33	
3.645	7.53	98	34	
3.461	8.35	112	35	
3.278	9.31	129	36	
3.094	10.45	149.5	37	
2.910	11.81	175	38	
2.727	13.45	209.5	39	
2.543	15.46	255	40	
2.360	17.96	317	41	
2.176	21.12	426	42	3.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #20 S. A. E.
Mirror Radius: .953 cm.
Mirror Coating: Aluminum
Ambient Temperature: 22.3 C.
Mass of Load: 163.5 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
8.602	1.35	0	0	
8.418	1.41	0.5	1	
8.235	1.48	1	2	
8.051	1.54	1.5	3	
7.868	1.62	2	4	
7.684	1.69	3	5	
7.500	1.78	4	6	
7.317	1.87	5	7	
7.133	1.97	6	8	
6.950	2.07	7	9	
6.766	2.18	8	10	
6.582	2.31	9	11	
6.399	2.44	11	12	
6.215	2.59	13	13	
6.032	2.75	15	14	
5.848	2.92	17	15	
5.664	3.12	19	16	
5.481	3.41	21	17	
5.297	3.56	23.5	18	
5.114	3.82	26.5	19	
4.930	4.12	29.5	20	
4.746	4.44	33	21	
4.563	4.80	37	22	
4.379	5.22	41.5	23	
4.196	5.68	47	24	
4.012	6.21	54	25	
3.828	6.82	62.5	26	
3.645	7.53	73	27	
3.461	8.35	84.5	28	
3.278	9.31	101.5	29	
3.186	9.86	110.5	29.5	
3.094	10.45	120.5	30	
3.002	11.10	132.5	30.5	
2.910	11.81	145.5	31	
2.819	12.59	162.5	31.5	
2.727	13.45	188	32	
2.635	14.41	208.5	32.5	
2.543	15.46	232.5	33	
2.451	16.64	258.5	33.5	
2.360	17.96	291.5	34	
2.268	19.45	330.5	34/5	
2.176	21.12	371.5	35	3.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #30 S. A. E. Ambient Temperature: 23.8 C.

Mirror Radius: 1.27 cm. Mass of Load: 283.4 gm.

Mirror Coating: Silver with CaF_2

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
8.897	1.26	0	0	
8.713	1.32	1	1	
8.529	1.38	2	2	
8.346	1.44	3	3	
8.162	1.50	4.5	4	
7.979	1.57	6	5	
7.795	1.66	7.5	6	
7.611	1.73	10	7	
7.428	1.81	12	8	
7.244	1.91	14	9	
7.061	2.01	16	10	
6.877	2.12	18.5	11	
6.693	2.23	21	12	
6.510	2.36	23.5	13	
6.326	2.50	27	14	
6.143	2.65	30	15	
5.959	2.82	34	16	
5.408	3.42	47	19	
5.225	3.66	52	20	
5.041	3.94	58	21	
4.857	4.24	65	22	
4.674	4.58	72	23	
4.490	4.96	81	24	
4.307	5.39	91	25	
4.123	5.88	101.5	26	
3.939	6.44	115	27	
3.756	7.09	130	28	
3.572	7.84	150	29	
3.389	8.70	173	30	
3.297	9.20	186	30.5	
3.205	9.74	202	31	
3.113	10.32	219	31.5	
3.021	10.96	239	32	
2.930	11.65	260	32.5	
2.838	12.42	288	33	
2.746	13.26	318	33.5	
2.654	14.20	352	34	
2.562	15.23	392	34.5	
2.471	16.38	440	35	
2.287	19.12	553	36	
2.195	20.75	633	36.5	
2.103	22.60	720	37	2.9
2.012	24.71	834	37.5	

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #30 S. A. E. Ambient Temperature: 22.7 C.
Mirror Radius: 1.27 cm. Mass of Load: 419.2 gm.
Mirror Coating: Silver with CaF

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
10.758	0.86	0	0	
10.574	0.89	1	1	
10.390	0.93	2	2	
10.207	0.96	3	3	
10.023	1.00	4	4	
9.840	1.03	5	5	
9.656	1.07	6	6	
9.472	1.11	7	7	
9.289	1.16	8	8	
9.105	1.21	9	9	
8.922	1.26	10	10	
8.738	1.31	11	11	
8.554	1.37	12	12	
8.371	1.43	14	13	
8.187	1.49	16.5	14	
8.004	1.56	18.5	15	
7.820	1.64	21	16	
7.636	1.72	23.5	17	
7.453	1.80	26	18	
7.269	1.89	28.5	19	
7.086	1.99	31	20	
6.902	2.10	34	21	
6.718	2.22	38	22	
6.535	2.34	42	23	
6.351	2.48	46	24	
6.168	2.63	51	25	
5.984	2.79	56	26	
5.800	2.97	62	27	
5.617	3.17	67	28	
5.433	3.39	74	29	
5.250	3.63	82.5	30	
5.066	3.90	91.5	31	
4.882	4.20	102	32	
4.699	4.53	114	33	
4.515	5.33	128	34	
4.332	5.33	144	35	
4.148	5.81	163	36	
3.964	6.36	184	37	
3.781	7.00	213	38	
3.597	7.73	246 ✓	39	
3.414	8.58	293	40	
3.230	9.59	371	41	
3.046	10.78	553	42	4.2

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #30 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF

Ambient Temperature: 22.9 C.
Mass of Load: 573.3 gm.

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
9.569	1.09	0	0	
9.385	1.14	1	1	
9.201	1.18	2	2	
9.018	1.23	3	3	
8.834	1.28	4	4	
8.651	1.34	5	5	
8.467	1.40	6	6	
8.283	1.46	7	7	
8.100	1.52	8	8	
7.916	1.60	9	9	
7.733	1.67	10	10	
7.549	1.76	11.5	11	
7.365	1.84	13	12	
7.182	1.94	14.5	13	
6.998	2.04	16	14	
6.815	2.15	18	15	
6.631	2.28	20	16	
6.447	2.41	22	17	
6.264	2.55	24	18	
6.080	2.71	26.5	19	
5.897	2.88	29.5	20	
5.713	3.06	32.5	21	
5.529	3.27	35.5	22	
5.346	3.50	39	23	
5.162	3.75	43	24	
4.979	4.03	48	25	
4.795	4.35	53	26	
4.611	4.70	58.5	27	
4.428	5.10	65	28	
4.244	5.56	71.5	29	
4.061	6.07	80	30	
3.877	6.65	89.5	31	
3.693	7.33	101	32	
3.510	8.12	115	33	
3.418	8.56	131.5	34	
3.326	9.04	142.5	34.5	
3.234	9.56	155	35	
3.143	10.13	170	35.5	
3.051	10.74	188	36	
2.959	11.42	212	36.5	
2.867	12.16	247.5	37	
2.775	12.97	296.5	37.5	
2.684	13.89	404	38	3.7

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #30 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23.6 C.
Mass of Load: 721.4 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
7.031	2.02	0	0	
6.848	2.13	1	1	
6.664	2.25	2	2	
6.480	2.38	3	3	
6.297	2.52	4.5	4	
6.113	2.68	6.5	5	
5.930	2.84	8	6	
5.746	3.03	10	7	
5.562	3.23	12.5	8	
5.379	3.46	16	9	
5.195	3.71	18.5	10	
5.012	3.98	22	11	
4.828	4.29	25.5	12	
4.644	4.64	29	13	
4.461	5.03	33	14	
4.277	5.47	38	15	
4.094	5.97	43	16	
3.910	6.54	49	17	
3.726	7.20	56.5	18	
3.543	7.97	65	19	
3.359	8.86	74	20	
3.176	9.92	86	21	
2.992	11.17	100	22	
2.808	12.68	117	23	
2.625	14.52	138	24	
2.533	15.59	151	24.5	
2.441	16.78	166.5	25	
2.349	18.12	183	25.5	
2.258	19.63	203	26	
2.166	21.32	226	26.5	
2.074	23.25	252.5	27	
1.982	25.46	284	27.5	
1.890	27.99	324	28	
1.799	30.92	377	28.5	
1.707	34.33	454	29	
1.615	38.35	581	29.5	
1.523	43.11	831	30	2.1

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #30 S. A. E. Ambient Temperature: 23.4 C.
Mirror Radius: .953 cm. Mass of Load: 95.8 gm.
Mirror Coating: Aluminum

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
11.889	0.71	0	0	
11.705	0.73	1	1	
11.521	0.75	2	2	
11.338	0.78	3	3	
11.154	0.80	4	4	
10.971	0.83	5	5	
10.787	0.86	6	6	
10.603	0.89	7	7	
10.420	0.92	8	8	
10.236	0.95	9	9	
10.053	0.99	10	10	
9.869	1.03	12	11	
9.685	1.07	13	12	
9.502	1.11	14	13	
9.318	1.15	15	14	
9.135	1.20	17	15	
8.951	1.25	19	16	
8.767	1.30	21	17	
8.584	1.36	23	18	
8.400	1.42	25	19	
8.217	1.48	27	20	
8.033	1.55	29	21	
7.849	1.62	31	22	
7.666	1.70	35	23	
7.482	1.79	39	24	
7.299	1.88	43	25	
7.115	1.98	47	26	
6.931	2.08	51	27	
6.748	2.20	56	28	
6.564	2.33	61	29	
6.381	2.46	67	30	
6.197	2.60	74	31	
6.013	2.77	83	32	
5.830	2.94	91	33	
5.646	3.14	101	34	
5.463	3.35	113	35	
5.279	3.59	125	36	
5.095	3.85	140	37	
4.912	4.15	158.5	38	
4.728	4.47	178	39	
4.545	4.84	202	40	
4.361	5.26	233	41	
4.177	5.73	269	42	
3.994	6.27	316	43	
3.810	6.89	387	44	
3.718	7.23	438	44.5	
3.627	7.60	496	45	5.0

APPENDIX II

TABULATED DATA PN TRANSIENT BEHAVIOR OF LUBRICATING OIL

Oil: #30 S. A. E. Ambient Temperature: 23.4 C.
Mirror Radius: .953 cm. Mass of Load: 163.5 gm.
Mirror Coating: Aluminum

h (microns)	$(1/h^2)\ x\ 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
11.855	0.71	0	0	
11.671	0.73	0.5	1	
11.487	0.76	1.0	2	
11.304	0.78	1.5	3	
11.120	0.81	2.0	4	
10.937	0.84	2.5	5	
10.753	0.87	3.0	6	
10.569	0.90	3.5	7	
10.386	0.93	4	8	
10.202	0.96	5	9	
10.019	1.00	6	10	
9.835	1.03	7	11	
9.651	1.07	8	12	
9.468	1.12	9	13	
9.284	1.16	10	14	
9.101	1.21	11	15	
8.917	1.26	12	16	
8.733	1.31	13	17	
8.550	1.37	15	18	
8.366	1.43	16	19	
8.183	1.49	17.5	20	
7.999	1.56	19.5	21	
7.815	1.63	21.5	22	
7.632	1.72	23.5	23	
7.448	1.80	25.5	24	
7.265	1.90	27.5	25	
7.081	2.00	30.5	26	
6.897	2.10	33.5	27	
6.714	2.22	36.5	28	
6.530	2.35	39.5	29	
6.347	2.48	43.5	30	
6.163	2.63	46.5	31	
5.979	2.80	50.5	32	
5.796	2.98	55.5	33	
5.612	3.18	60.5	34	
5.429	3.39	66.5	35	
5.245	3.64	73.5	36	
5.061	3.90	81.5	37	
4.878	4.20	90.5	38	
4.694	4.54	100.5	39	
4.511	4.92	112.5	40	
4.327	5.34	126.5	41	
4.143	5.83	142.5	42	
3.960	6.38	164.5	43	
3.776	7.01	198.5	44	
3.593	7.75	250.5	45	
3.409	8.61	335.5	46	4.7

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E. Ambient Temperature: 22.8 C.

Mirror Radius: 1.27 cm. Mass of Load: 105.5 gm.

Mirror Coating: Silver with CaF_2

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
10.716	0.87	0	0	
10.533	0.90	2.5	1	
10.350	0.93	6	2	
10.167	0.97	9.5	3	
9.984	1.00	13.5	4	
9.800	1.04	17.5	5	
9.617	1.08	22	6	
9.434	1.12	27	7	
9.251	1.17	32	8	
9.068	1.22	37	9	
8.884	1.27	42.5	10	
8.701	1.32	49	11	
8.518	1.38	55.5	12	
8.335	1.44	63	13	
8.152	1.51	71	14	
7.968	1.58	80	15	
7.785	1.65	89	16	
7.602	1.73	99	17	
7.419	1.82	110.5	18	
7.236	1.91	123	19	
7.052	2.01	137	20	
6.961	2.06	145	20.5	
6.869	2.12	152	21	
6.778	2.18	160.5	21.5	
6.686	2.24	169.5	22	
6.594	2.30	178	22.5	
6.503	2.37	188	23	
6.411	2.43	198.5	23.5	
6.320	2.50	211	24	
6.228	2.58	222	24.5	
6.136	2.66	235	25	
6.045	2.74	248	25.5	
5.953	2.82	263	26	
5.862	2.88	278	26.5	
5.770	3.00	294.5	27	
5.678	3.10	312	27.5	
5.587	3.20	331	28	
5.495	3.31	354	28.5	
5.404	3.43	377	29	
5.312	3.54	399	29.5	
5.220	3.67	423	30	
5.129	3.80	449	30.5	
5.037	3.94	479	31	
4.946	4.09	511	31.5	
4.854	4.24	544	32	
4.762	4.41	582	32.5	
4.671	4.57	626	33	
4.579	4.77	748	33.5	
4.488	4.97	876	34	6.2

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 23.0 C.
Mass of Load: 197.0 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
9.694	1.064	0	0	
9.511	1.11	4	1	
9.328	1.12	8	2	
9.144	1.20	12	3	
8.961	1.25	16	4	
8.778	1.30	21	5	
8.595	1.35	26	6	
8.412	1.41	32	7	
8.228	1.48	38	8	
8.045	1.55	44	9	
7.862	1.62	50	10	
7.679	1.70	58	11	
7.496	1.78	66	12	
7.312	1.87	75	13	
7.129	1.97	84.5	14	
6.946	2.07	95	15	
6.763	2.19	106.5	16	
6.580	2.31	120	17	
6.396	2.44	134.5	18	
6.213	2.59	150	19	
6.030	2.78	168	20	
5.847	2.93	188	21	
5.664	3.12	211	22	
5.572	3.22	223	22.5	
5.480	3.33	236.5	23	
5.389	3.44	250	23.5	
5.297	3.56	266	24	
5.206	3.69	282.5	24.5	
5.114	3.82	299.5	25	
5.022	3.96	317.5	25.5	
4.931	4.11	338	26	
4.839	4.27	359	26.5	
4.748	4.44	383	27	
4.656	4.61	411	27.5	
4.564	4.80	442	28	
4.473	5.00	482.5	28.5	
4.381	5.21	530	29	
4.290	5.43	620	29.5	
4.198	5.67	1026	30	5.8

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E. — Ambient Temperature: 23.0 C.
Mirror Radius: 1.27 cm. — Mass of Load: 283.4 gm.
Mirror Coating: Silver with CaF

h (microns)	$(1/h^2) \times 10^{-6}$ (cm.$^{-2}$)	t (sec.)	n	N
11.189	0.79	0	0	
11.005	0.83	2	1	
10.922	0.84	4	2	
10.739	0.87	6.5	3	
10.556	0.90	9	4	
10.373	0.93	12	5	
10.189	0.99	15	6	
10.006	1.04	18	7	
9.823	1.04	21	8	
9.640	1.08	24.5	9	
9.457	1.12	28	10	
9.273	1.16	31.5	11	
9.090	1.21	35.5	12	
8.907	1.26	40	13	
8.724	1.31	44	14	
8.541	1.37	49	15	
8.357	1.43	54	16	
8.174	1.50	59.5	17	
7.991	1.57	65.5	18	
7.808	1.64	72	19	
7.625	1.72	79	20	
7.441	1.81	87	21	
7.258	1.89	95	22	
7.075	2.00	104	23	
6.892	2.11	114	24	
6.709	2.22	124	25	
6.525	2.35	136	26	
6.342	2.49	149.5	27	
6.159	2.64	164	28	
5.976	2.80	179.5	29	
5.793	2.98	197.5	30	
5.609	3.18	218	31	
5.426	3.40	241	32	
5.243	3.64	267	33	
5.060	3.91	296	34	
4.877	4.21	329	35	
4.693	4.54	367	36	
4.510	4.92	411	37	
4.327	5.34	461.5	38	
4.144	5.82	528.5	39	
3.961	6.38	597	40	
3.777	7.01	678	41	
3.594	7.74	773	42	
3.411	8.60	885	43	
3.228	9.63	1018	44	
3.045	10.79	1179	45	
2.861	12.21	1303	46	
2.678	13.94	1732	47	3.7

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E. Ambient Temperature: 22.9 C.
Mirror Radius: 1.27 cm. Mass of Load: 573.3 gm.
Mirror Coating: Silver with CaF

h (microns)	$(1/h^2)$ x 10^{-6} ($cm.^{-2}$)	t (sec.)	n	N
9.761	1.05	0	0	
9.578	1.09	1	1	
9.394	1.13	2	2	
9.211	1.18	3	3	
9.028	1.23	4	4	
8.845	1.28	5	5	
8.662	1.33	6	6	
8.478	1.39	7	7	
8.295	1.45	8	8	
8.112	1.52	9	9	
7.929	1.59	11	10	
7.746	1.67	13	11	
7.562	1.75	15	12	
7.379	1.84	17	13	
7.196	1.93	19	14	
7.013	2.03	21	15	
6.830	2.15	23	16	
6.646	2.26	25	17	
6.463	2.39	28	18	
6.280	2.54	32	19	
6.097	2.69	36	20	
5.914	2.86	40	21	
5.730	3.05	45	22	
5.547	3.25	50	23	
5.364	3.48	55	24	
5.181	3.73	61.5	25	
4.998	4.00	69.5	26	
4.814	4.32	78	27	
4.631	4.66	88.5	28	
4.448	5.06	99.5	29	
4.356	5.27	105.5	29.5	
4.265	5.50	112.5	30	
4.173	5.74	120	30.5	
4.082	6.00	128.5	31	
3.990	6.28	137	31.5	
3.898	6.58	147	32	
3.807	6.90	157	32.5	
3.715	7.25	169	33	
3.624	7.62	182	33.5	
3.532	8.02	199	34	
3.440	8.45	210	34.5	
3.349	8.92	241	35	
3.257	9.43	367	35.5	4.5

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E. Ambient Temperature: 22.9 C.

Mirror Radius: 1.27 cm. Mass of Load: 419.2 gm.

Mirror Coating: Silver with CaF

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
10.397	0.93	0	0	
10.214	0.96	1	1	
10.031	0.99	2	2	
9.848	1.03	3	3	
9.665	1.07	4	4	
9.481	1.07	4	4	
9.298	1.11	5	5	
9.115	1.16	6	6	
8.932	1.20	8	7	
8.749	1.25	10	8	
8.565	1.31	12	9	
8.382	1.36	14	10	
8.199	1.42	16	11	
8.016	1.49	18	12	
7.833	1.56	20.5	13	
7.649	1.63	23	14	
7.466	1.71	26	15	
7.283	1.79	29	16	
7.100	1.89	32	17	
6.917	1.98	36	18	
6.733	2.09	40	19	
6.550	2.21	44	20	
6.367	2.33	49	21	
6.184	2.47	54.5	22	
6.001	2.62	60	23	
5.817	2.78	66	24	
5.634	3.15	80	26	
5.451	3.37	88.5	27	
5.268	3.60	98.5	28	
5.176	3.73	104.5	28.5	
5.085	3.87	110.5	29	
4.993	4.01	116.5	29.5	
4.901	4.16	123.5	30	
4.810	4.32	131.5	30.5	
4.718	4.49	139.5	31	
4.627	4.67	148.5	31.5	
4.535	4.86	158.5	32	
4.443	5.07	169.5	32.5	
4.352	5.28	180.5	33	
4.260	5.51	191.5	33.5	
4.169	5.76	205.5	34	
4.077	6.02	220.5	34.5	
3.985	6.30	238	35	
3.894	6.60	261	35.5	
3.802	6.92	295	36	
3.711	7.26	346.5	36.5	
3.619	7.64	568.5	37	5.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E. Ambient Temperature: 23.0 C.

Mirror Radius: 1.27 cm. Mass of Load: 721.4 gm.

Mirror Coating: Silver with CaF

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
10.551	0.90	0	0	
10.368	0.93	0.5	1	
10.185	0.96	1	2	
10.002	1.00	1.5	3	
9.818	1.04	2	4	
9.636	1.08	3	5	
9.452	1.12	4	6	
9.269	1.16	5	7	
9.086	1.21	6	8	
8.902	1.26	7	9	
8.719	1.32	8	10	
8.536	1.37	9	11	
8.353	1.43	10	12	
8.170	1.50	11	13	
7.986	1.57	12.5	14	
7.803	1.64	14	15	
7.620	1.72	15.5	16	
7.437	1.81	17	17	
7.254	1.90	19	18	
7.070	2.00	21.5	19	
6.887	2.11	24	20	
6.704	2.23	26.5	21	
6.521	2.35	29	22	
6.338	2.49	32	23	
6.154	2.64	35.5	24	
5.971	2.81	39	25	
5.788	2.98	43	26	
5.605	3.18	47	27	
5.422	3.40	52	28	
5.238	3.64	57.5	29	
5.055	3.91	63.5	30	
4.872	4.21	70	31	
4.689	4.55	78	32	
4.506	4.93	86.5	33	
4.322	5.35	96.5	34	
4.139	5.84	107.5	35	
3.956	6.38	121	36	
3.773	7.03	137.5	37	
3.590	7.76	145	38	
3.498	8.17	157.5	38.5	
3.406	8.62	169	39	
3.315	9.10	183.5	39.5	
3.223	9.63	203	40	
3.132	10.20	238.5	40.5	
3.040	10.82	502	40.9	4.2

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22.8 C.
Mass of Load: 881.7 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
8.030	1.55	0	0	
7.847	1.62	0.5	1	
7.663	1.70	1	2	
7.480	1.79	1.5	3	
7.297	1.88	2	4	
7.114	1.98	3	5	
6.931	2.08	4	6	
6.747	2.20	5	7	
6.564	2.32	6	8	
6.381	2.46	7	9	
6.198	2.60	8.5	10	
6.015	2.76	9	11	
5.831	2.94	10.5	12	
5.648	3.14	12.5	13	
5.465	3.35	14.5	14	
5.282	3.56	16.5	15	
5.099	3.85	19	16	
4.915	4.14	21.5	17	
4.732	4.47	24.5	18	
4.549	4.83	28.5	19	
4.366	5.25	32.5	20	
4.178	5.73	37.5	21	
3.994	6.27	42.5	22	
3.811	6.88	50.5	23	
3.628	7.60	59.5	24	
3.445	8.43	68.5	25	
3.262	9.40	81.5	26	
3.170	9.95	88.5	26.5	
3.078	10.55	99.5	27	
2.987	11.21	117	27.5	
2.895	11.93	160	28	4.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E.
Mirror Radius: 1.27 cm.
Mirror Coating: Silver with CaF
Ambient Temperature: 22.8 C.
Mass of Load: 1176.8 gm.

n = fringe order
N = total number of fringes between blue and green Mercury lines

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
7.991	1.57	0	0	
7.808	1.64	0.5	1	
7.625	1.72	1	2	
7.441	1.81	1.5	3	
7.258	1.90	2	4	
7.075	2.00	3	5	
6.892	2.11	4	6	
6.709	2.22	5	7	
6.525	2.35	6	8	
6.342	2.49	7.5	9	
6.159	6.64	9	10	
5.976	2.80	10.5	11	
5.793	2.98	12	12	
5.609	3.18	14	13	
5.426	3.40	16	14	
5.243	3.64	18.5	15	
5.060	3.91	21	16	
4.877	4.21	24	17	
4.693	4.54	27	18	
4.510	4.92	31	19	
4.327	5.34	35.5	20	
4.144	5.82	40.5	21	
3.961	6.38	46	22	
3.777	7.01	53	23	
3.594	7.74	60	24	
3.411	8.60	69.5	25	
3.228	9.60	80	26	
3.045	10.79	93.5	27	
2.953	11.47	102.5	27.5	
2.861	12.21	114.5	28	
2.770	13.04	134	28.5	
2.678	13.94	270	28.8	3.7

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E.
Mirror Radius: .953 cm.
Mirror Coating: Aluminum

Ambient Temperature: 23.1 C.
Mass of Load: 95.8 gm.

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
12.413	0.65	0	0	
12.230	0.67	2	1	
12.046	0.69	3.5	2	
11.863	0.71	6	3	
11.680	0.73	8	4	
11.497	0.76	9.5	5	
11.314	0.78	11	6	
11.130	0.81	13	7	
10.947	0.84	14.5	8	
10.764	0.86	17	9	
10.581	0.89	20	10	
10.398	0.93	22	11	
10.214	0.96	25.5	12	
10.031	0.99	29	13	
9.848	1.03	32	14	
9.665	1.07	36	15	
9.482	1.11	40	16	
9.298	1.16	44	17	
9.115	1.20	48	18	
8.932	1.25	52	19	
8.749	1.31	57	20	
8.566	1.36	63	21	
8.382	1.42	68.5	22	
8.199	1.49	75	23	
8.016	1.56	81.5	24	
7.833	1.63	88.5	25	
7.650	1.71	96	26	
7.466	1.79	104.5	27	
7.283	1.89	113.5	28	
7.100	1.98	122.5	29	
6.917	2.09	132.5	30	
6.734	2.21	143.5	31	
6.550	2.33	155.5	32	
6.367	2.47	170.5	33	
6.184	2.62	184.5	34	
6.001	2.78	200.5	35	
5.818	2.96	217.5	36	
5.634	3.15	237.5	37	
5.451	3.37	258.5	38	
5.268	3.60	282.5	39	
5.085	3.87	308.5	40	
4.901	4.16	337.5	41	
4.718	4.49	369.5	42	
4.535	4.86	407.5	43	
4.352	5.28	448.5	44	
4.169	5.76	493.5	45	
3.985	6.30	550.5	46	
3.802	6.92	607.5	47	
3.619	7.64	672.5	48	5.0

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E.
Mirror Radius: .953 cm.
Mirror Coating: Aluminum

Ambient Temperature: 23.0 C.
Mass of Load: 109.9 gm.

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
11.333	0.78	0	0	
11.150	0.80	2	1	
10.967	0.83	4	2	
10.784	0.86	6	3	
10.600	0.89	8	4	
10.417	0.92	10	5	
10.234	0.96	12	6	
10.051	0.99	16	7	
9.868	1.03	19	8	
9.684	1.07	22	9	
9.501	1.108	25	10	
9.318	1.15	28.5	11	
9.135	1.20	32.5	12	
8.952	1.25	36	13	
8.768	1.30	40.5	14	
8.685	1.33	44.5	15	
8.502	1.38	49.5	16	
8.319	1.45	54.5	17	
8.136	1.51	59.5	18	
7.952	1.58	65.5	19	
7.769	1.66	72	20	
7.586	1.74	79	21	
7.403	1.83	86	22	
7.220	1.92	94.5	23	
7.036	2.02	102.5	24	
6.853	2.13	112.5	25	
6.670	2.25	122.5	26	
6.487	2.38	133.5	27	
6.304	2.52	144.5	28	
6.120	2.67	158.5	29	
5.937	2.84	173.5	30	
5.754	3.02	187.5	31	
5.571	3.22	207	32	
5.388	3.45	227	33	
5.204	3.69	248.5	34	
5.021	3.97	273.5	35	
4.838	4.27	300.5	36	
4.655	4.62	330.5	37	
4.472	5.00	365.5	38	
4.288	5.44	404.5	39	
4.105	5.93	451.5	40	
3.922	6.50	503.5	41	
3.739	7.15	562.5	42	
3.556	7.91	633.5	43	
3.372	8.79	718.5	44	
3.189	9.83	821.5	45	
3.006	11.07	948.5	46	
2.823	12.55	1105.5	47	3.9

APPENDIX II

TABULATED DATA ON TRANSIENT BEHAVIOR OF LUBRICATING OILS

Oil: #50 S. A. E.
Mirror Radius: .953 cm.
Mirror Coating: Aluminum

Ambient Temperature: 23.1 C.
Mass of Load: 169.7 gm.

h (microns)	$(1/h^2) \times 10^{-6}$ ($cm.^{-2}$)	t (sec.)	n	N
11.689	0.73	0	0	
11.506	0.76	1	1	
11.323	0.78	2	2	
11.140	0.81	3	3	
10.956	0.83	4	4	
10.773	0.86	5	5	
10.590	0.89	6	6	
10.407	0.92	7.5	7	
10.224	0.96	9	8	
10.040	0.99	10.5	9	
9.857	1.03	12	10	
9.674	1.07	13.5	11	
9.491	1.11	15.5	12	
9.308	1.15	17.5	13	
9.124	1.20	19.5	14	
8.941	1.25	21.5	15	
8.758	1.30	23.5	16	
8.575	1.36	25.5	17	
8.392	1.42	28	18	
8.208	1.48	31	19	
8.025	1.55	34	20	
7.842	1.63	37	21	
7.659	1.71	41	22	
7.476	1.79	45	23	
7.292	1.88	49	24	
7.109	1.98	54	25	
6.926	2.09	59	26	
6.743	2.20	64	26	
6.560	2.32	70	28	
6.376	2.46	77	29	
6.193	2.61	84	30	
6.010	2.77	92	31	
5.827	2.95	101	32	
5.643	3.14	110.5	33	
5.460	3.35	121	34	
5.277	3.59	134	35	
5.094	3.85	148	36	
4.910	4.15	164	37	
4.727	4.48	180	38	
4.544	4.84	200	39	
4.361	5.26	223	40	
4.178	5.73	248	41	
3.994	6.27	278	42	
3.811	6.89	313	43	
3.628	7.60	353	44	
3.445	8.43	404	45	
3.262	9.40	462	46	
3.078	10.55	538	47	
2.895	11.93	615	48	4.0

APPENDIX III

TABULATED DATA ON STABLE FILM THICKNESSES

#20 S. A. E. Oil - Mirrors: Silver with CaF, 1.27 cm. Radius

M Mass of Load (gm.)	Mg/R^2 Nominal Load Pressure (psi)	N Total Fringes	Time Under Load	h_s Stable Film Thickness (microns)
105.5	0.30	6.1	14 hours	4.42
283.4	0.80	6.2	87 hours	4.50
1176.8	3.31	2.3	1 hour	1.67
1976.8	5.56	1.9	1.67 hrs	1.38
2684.8	7.55	1.7	2 hours	1.23
105.5*	0.30*	2.1*	5 min.*	1.52*

#20 S. A. E. Oil - Mirrors: Aluminum, Radius = .953 cm.

6.4	0.03	11.0	2 hours	7.98
311.6	1.56	2.7	18 hours	1.95
471.9	2.36	2.3	4 hours	1.67
767.1	3.84	1.85	2 hours	1.34
1475.1	7.38	1.2	17 hours	0.87
2275.1	11.38	1.0	4 hours	0.73
767.1*	3.84*	1.1*	10 min.*	0.80*
311.6*	1.56*	1.2*	10 min.*	0.87*
6.4*	0.03*	1.6*	3 hours*	1.16*

#50 S. A. E. Oil - Mirrors: Silver with CaF, Radius = 1.27 cm.

105.5	0.30	2.3	18 hours	1.67
197.0	0.55	3.8	14 hours	2.75
283.4	0.80	3.3	15 hours	2.39
419.2	1.18	3.75	20 hours	2.71
721.4	2.03	3.8	14 hours	2.75
1176.8	3.31	3.7	16 hours	2.68
1176.8	3.31	1.7	3 hours	1.23
1484.8	4.17	1.8	1 hour	1.30
1884.8	5.30	1.7	1 hour	1.23
2684.8	7.55	1.6	6.5 hours	1.16
197.0*	0.55*	2.0*	72 hours*	1.45*
105.5*	0.30*	2.1*	72 hours*	1.52*

#50 S. A. E. Oil - Mirrors: Aluminum, Radius = .953 cm.

311.6	1.56	1.5	18 hours	1.09
767.1	3.84	1.1	1 hour	0.80
1075.1	5.38	1.0	1 hour	0.72
2275.1	11.38	1.0	1 hour	0.72
9.4*	0.05*	1.5*	10 min.*	1.09*

*Relaxation upon removal of portions of load.